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Lightness and Brightness Scaling and the Effect of Stimulus Realism

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Abstract

The human visual system uses information on the light that enters the retina from objects in our environment to infer different physical properties of these objects such as surface reflectance. It is not yet understood under which conditions the visual system only measures and perceives the luminance of objects and under which conditions it can tell apart physical properties of objects such as surface reflectance. Previous studies such as by Maertens, Wichmann, and Shapley (2015) and by Murray (2021) show that context and realism are conditions in which the visual system can differentiate between luminance (brightness) and surface reflectance (lightness). Many studies that discuss this topic often use unrealistic stimuli, resulting in a limited understanding of which specific factors in realistic stimuli are essential for the visual system to judge lightness and brightness. Therefore, the present study wants to investigate if certain parameters in realistic stimuli influence lightness and brightness judgments. We used 3D photo-realistic scenes and investigated several parameters such as blurriness, lighting gradients, the simultaneous contrast effect, and the instructional tasks to see if these had an effect on lightness and brightness judgments. We used multidimensional scaling methods such as the method of triplets and the soft ordinal embedding algorithm to map these judgments of observers. Results show that different instructional tasks and lighting gradients within realistic scenes did not affect lightness judgment, suggesting that this information may not be necessary for the visual system to judge lightness. However, realistic scenes, blurred versions of realistic scenes, and the simultaneous contrast effect did affect lightness judgments. In these conditions, stimuli were perceived more similarly by their reflectance values than luminance values, suggesting that the visual system can use these cues to better extract properties like the surface reflectance of objects.

Declaration of Authorship

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Edward Beach

Edward Beach

Contents

1 Introduction

In vision science, studying how our visual system processes incoming light that enters the retina plays an important role. The Adelson checkerboard in Figure 1 is an example of the ambiguous manner the human visual system can break down light (Adelson, 1995). When observers are asked to judge whether checks A or B on the left checkerboard are brighter, the typical answer is that check B is brighter. However, looking at the right checkerboard, one can see that checks A and B have the same brightness.

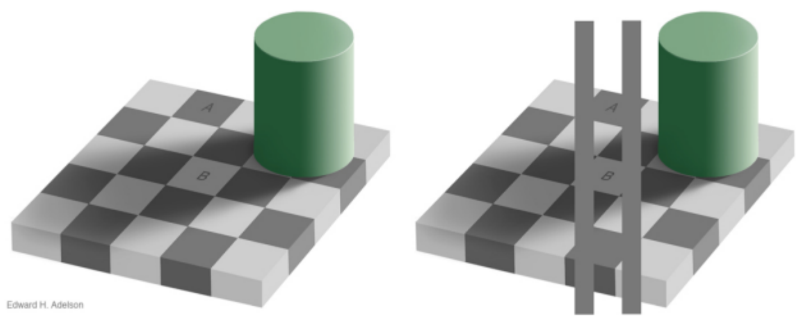


Figure 1: Adelson Checkerboard, left: check B looks brighter than check A, right: check A has the same brightness as check B (Adelson, 1995).

To understand what can contribute to this illusion and to also gain a better understanding of the current research on this topic, it is vital to first introduce some basic concepts related to luminance, illumination, reflectance, lightness, and brightness, and their interrelationships. Luminance can be described by the intensity of light emitted from a surface per unit area in a given direction (Murray, 2021). On the checkerboard, this is the amount of light that is emitted by a given check and reaches the retina. Illumination is the amount of light that is emitted by a light source and reflectance is the proportion of light incident on a surface that is reflected from it (Kingdom, 2011). For example, check A is being hit by more illumination than check B, since check B lies in the shadow of the cylinder. The black check A absorbs more light than check B, thus it has lower reflectance than check B and vice versa. Luminance is determined by the physical properties of illumination and reflectance. The relationship between luminance, illumination, and reflectance on an image with pixel coordinates (x, y) can be described by the simple formula below:

$$L(x, y) = I(x, y) \cdot R(x, y)$$

where L stands for luminance, I for illumination and R for reflectance (Kingdom, 2011). Lightness refers to the visual system's *perceived reflectance* and brightness refers to the visual system's *perceived luminance* (Kingdom, 2011). When the visual system perceives the same lightness under differing illuminations this is called lightness constancy (Kingdom, 2011).

With these terms, we can now describe the illusion that happens on the left Adelson checkerboard more precisely. Check A has low reflectance and high illumination, whereas check B has low illumination and high reflectance. When calculating the product of illumination and reflectance for both checks they have the same luminance. One possible explanation for the differing perception of the two squares is that the visual system judges lightness on the left checkerboard and brightness on the right checkerboard. Another explanation, which does not necessarily exclude the previous one, is the simultaneous brightness contrast effect, where the stimulus appears brighter if the surround is dark and darker if the surround is bright (Maertens et al., 2015). This effect can be seen in Figure 2.

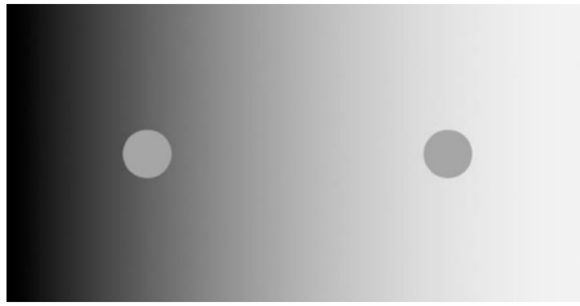


Figure 2: Example of the simultaneous contrast effect: Both circles have the same luminance, however, the circle on the left appears brighter and the circle on the right appears darker due to the contrast to their surround (Sinha et al., 2020).

It is up to debate when the visual system breaks down light into its separate properties such as on the left checkerboard and when the visual system only "measures" and analyzes the luminance of an object such as with the checks on the right checkerboard. One factor that could influence when we perceive lightness and brightness is the amount of realism of a stimulus (Murray, 2021). For example, on the left checkerboard, the shadow of the cylinder object could act as a realistic cue for the visual system, whereas on the right checkerboard, the realism of the shadow is interrupted by the grey lines surrounding the check. Could this mean that the visual system is more able to extract different properties of light if it has more realistic cues? One problem with many studies that involve the topic of lightness and brightness is that the stimuli are often very unrealistic or artificial and the effects of realism cannot properly be inferred, such as studies on the White's effect or the previously mentioned simultaneous contrast effect (Sinha et al., 2020; White, 1979). However, Murray (2021) states that the visual system may be able to use cues in realistic scenes such as lighting conditions to infer lightness. A previous Bachelor's thesis, therefore, attempted to investigate lightness and brightness in 3D photo-realistic scenes such as in Figure 3 (Barsukov, 2022).

Figure 3: Realistic stimulus that can be used to investigate its effects on lightness and brightness (Barsukov, 2022).

The study found that informed observers judged the discs differently based on whether they were asked to judge their lightness or brightness. Further, a study by Maertens and Wichmann (2013) showed that discrimination thresholds in modified versions of the Adelson checkerboard can be affected by apparent lightness, not just luminance. Thus, both the studies of Maertens and Wichmann (2013) and Barsukov (2022) suggest that the realism of a stimulus can influence our lightness and brightness judgments. These findings motivated the central questions of the present thesis: Why can our visual system judge lightness differently in more complex stimuli compared to simple stimuli such as White's effect (White, 1979)? Are there other cues, aside from surrounding context as found in the study of Maertens et al. (2015), that play a role? Could different degrees of realism, with varying amounts of texture and lighting that resemble our natural environment, affect our lightness and brightness judgments? To investigate these questions, our study used 3D photo-realistic scenes and psychometric scaling methods to investigate the effects of realism on lightness and brightness. Specifically, we used the method of triplets where three stimuli of different intensities were presented simultaneously, and the observer had to judge which of the left or right stimuli appeared more similar to the stimulus in the middle. For example, in the 3D photo-realistic scene shown in Figure 3, the observer had to judge which of the left or right discs appeared to have a more similar lightness or brightness to the disc in the middle. We analyzed the observer's responses to the triplets using ordinal embedding algorithms, which can arrange their responses in a plot based on their Euclidean distance, representing how differently the observers perceived the triplets (Terada & Luxburg, 2014). Depending on the "degree" of realism and whether the observer was asked to judge lightness and brightness one would expect these ordinal embeddings to differ from each other systematically if these factors indeed had an influence. Stimuli that were used in this study were based on a living room scene. The following sections will show which previous study results were attempted to be replicated, which factors of realism were investigated, and the expected results for each factor.

1.1 Lightness and brightness judgment in realistic scenes

Our first research question aimed to replicate the differences in lightness and brightness judgments in realistic scenes. A previous study using multidimensional scaling found that when observers were asked to judge the lightness of different stimuli, the perception of these stimuli was ordered in a specific way, as shown in Figure 4 (Logvinenko & Maloney, 2006). In Figure 4, the first index of each data point represents the stimulus' reflectance value, and the second index represents the stimulus' illumination value. The Euclidean distance between two points indicates the degree of difference in perception by the observer. One can see that data points with the same reflectance are located on the same radii, while data points with the same illumination are located on the same concentric arcs.

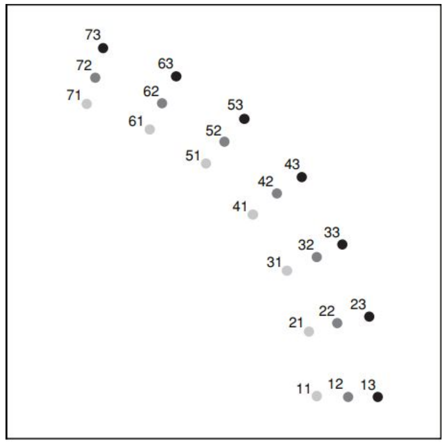


Figure 4: Results of the study by Logvinenko and Maloney (2006): stimuli with the same reflectances lie along the same radii, while stimuli with the same illumination lie along the same concentric arcs.

If realism enables the visual system to be able to distinguish between lightness and brightness, one would expect that if observers are asked to judge lightness in realistic scenes, their ordinal embeddings would mimic that of the results in Figure 4. Further, one would expect if observers are asked to judge brightness in realistic scenes, that data points would align along their grey value instead of their reflectance. In unrealistic scenes with uniform backgrounds, lightness and brightness should be judged identically since the visual system lacks contextual cues for extracting information about lightness.

1.2 Effect of instructions on lightness and brightness

When investigating the effects of realism on lightness and brightness, we wanted to rule out that solely having different instructions affect how observers judge lightness and brightness in realistic scenes. A previous study by Arend and Spehar (1993) raised concerns that in many lightness and brightness studies tasks of observers were "too vaguely defined to allow measurement of perceived surface colors.". We wanted to address this issue by using more specific instructions for our triplet tasks: for lightness tasks, we asked observers to judge which *material* looked more similar to the middle stimulus, and for brightness tasks, we asked which *stimulus* looked more similar to the middle stimulus. When the scene was unrealistic, we hypothesized that the visual system would not be able to extract information about reflectance properties and therefore, responses to the two different instructions would be indistinguishable.

1.3 Degrees of realism and lightness

The results of Maertens et al. (2015) showed that using modified versions of the Adelson checkerboard, which are more realistic stimuli, made it easier for the visual system to judge apparent lightness. In contrast, Barsukov (2022) found that in unrealistic scenes with uniform grey backgrounds, the visual system could not distinguish between lightness and brightness. How realistic are the stimuli used in the study by Maertens et al. (2015) really? Would adding additional cues, such as lamps that indicate where the light is coming from, increase the "degree" of realism? Can the visual system use these additional cues to more easily extract properties like surface reflectance? We, therefore, aimed to investigate how realistic stimuli affect lightness judgments by examining three different degrees of realism: degree 1 being an unrealistic scene, degree 2 being a slightly realistic scene such as a blurred version of a 3D photo-realistic scene, and degree 3 being fully realistic scenes such as unmodified versions of 3D photo-realistic scenes. We expected to observe a noticeable difference in the perception of lightness between the unrealistic and blurred realistic conditions and a noticeable difference in perception between the blurred realistic and fully realistic conditions. The biggest difference in the judgment of lightness and brightness was expected to be between the unrealistic and fully realistic conditions.

1.4 Lighting gradients within realistic scenes

Another factor of realism we wanted to investigate was lighting gradients within 3D photo-realistic scenes. In the example of Figure 3, the grey values on the discs were artificially pasted onto each pixel, resulting in all the pixels possessing the same grey value. However, realistic discs would contain a gradient, which may allow for slight differences in grey values caused by the lighting in the scene. According to Barsukov (2022), this lighting gradient could however help the visual system to judge lightness more easily. Therefore, we wanted to examine whether the visual system could judge lightness more easily when the lighting gradient was preserved compared to when it was removed.

1.5 Simultaneous contrast effect and realism

The final research question of this study was the influence of the simultaneous contrast effect in both realistic and unrealistic scenes on lightness and brightness. The study by Maertens et al. (2015) states that "it is well known that the lightness of an image region is influenced by the luminances of the regions that surround it". The question is how strong this effect is in realistic scenes and whether the visual system can use the surround reflectance of a stimulus as a cue to infer lighting conditions and more easily judge lightness. To investigate this, our study changed the surround reflectance of the annulus in 3D photo-realistic scenes to varying degrees. When the surround reflectance of the annulus is 0%, the visual system should not be able to use this additional cue to extract lightness. However, when the surround reflectance is slightly higher, we expected the visual system to use it as a cue to more easily judge lightness.

Thus, the goal of our study was to replicate previous results and explore the influence of different factors of realism on lightness and brightness using psychometric scaling methods. In the next chapter, we will provide an overview of the stimuli used in our study and explain how the experiments for the different research questions were set up.

2 Methods

2.1 Stimuli

The stimuli of the experiment consisted of 3D photo-realistic scenes of a living room as seen in Figure 5. The living room contained three square patches with a square dark frame (annulus) surrounding each square. Three individual lamps on the ceiling illuminated each square. The reflectance of each square and the illumination of each lamp could be changed independently from one another.

Figure 5: Physically Realistic scene of a living room used as stimulus. The reflectance of the squares and illumination of the three lamps on the ceiling can be changed independently.

These photo-realistic scenes were created within the Neural Information Processing Group of Tübingen with the software Blender (Community, 2018) and rendered in the research-oriented program Mitsuba 3 (Jakob et al., 2022). After the rendering process, the RGB values of the scenes were converted to greyscale using the YUV formula $Y = 0.299 \cdot R + 0.578 \cdot G + 0.114 \cdot B$. The scenes were then converted to *XML* files, where the illumination values from each lamp and the reflectance of each square could be adjusted. The illumination values were normalized so that a reflectance of one and illumination of one resulted in white for all three squares. In total, six different reflectances for the squares and three different illuminations for the lamps were used. The exact combinations of reflectances and illuminations and their respective grey values and luminances can be seen in Table 1. Combinations resulting in a grey value greater than one were excluded from the experiment.

Table 1: Grey values and their respective luminances used in the experiment.

	Illumination [in %] with grey values			**Illumination in [%] with luminance in $\frac{cd}{m^2}$**		
Reflectance [in %]	**29**	**100**	**310**	**29**	**100**	**310**
2.7	0.0094	0.0272	0.0808	2.69	7.04	20.17
11	0.0373	0.1066	0.3610	9.52	26.48	77.74
25	0.0832	0.2395	0.7097	20.76	59.02	174.13
44	0.1476	0.4258		36.52	104.63	
69	0.2320	0.6654		57.18	163.28	
100	0.3347	0.961		82.32	235.65	

Each square in a triplet consisted of one of the reflectance and illumination values from the table. Additionally, a given triplet did not contain two or more squares that had both identical reflectance and illumination values. A total of 2730 triplets were created by combining all possible combinations of reflectance and illumination values. To calculate a two-dimensional ordinal embedding, the following formula considers the number of dimensions and values and determines as a rule of thumb how many stimuli are needed: $2 \cdot d \cdot n \cdot log_2(n)$ (Haghiri, Wichmann, & von Luxburg, 2020), where d stands for the dimension and n for the number of reflectance and illumination values. Thus, a total number of at least $2 \cdot 15 \cdot log_2(15) = 118$ triplets were required to calculate a two-dimensional ordinal embedding. For every experiment, the same 600 triplets were randomly sampled from the total 2730 triplets for every condition.

In order to answer the underlying research questions the study consisted of several experimental conditions, each changing the parameters of the previously described photo-realistic stimuli to some degree. The experimental conditions consisted of the Physically Realistic condition, the Semi-Realistic condition, the blurred Semi-Realistic condition (Gaussian), the Uniform condition, and the Simultaneous Contrast condition. The next section will describe exactly which parameters were changed for each of these conditions.

Physically Realistic condition

The first experimental condition was the Physically Realistic condition, which used stimuli from the rendering shown in Figure 5. In this condition, the squares had a natural lighting gradient caused by the illumination of the lamps, resulting in each pixel of every square being slightly different from one another in their grey value. The pixel values for every square could differ by a standard deviation of 5.5%.

Semi-Realistic condition

In the Semi-Realistic condition, the natural gradient was removed by calculating the mean grey pixel value for each square and pasting it onto every pixel in the given square. The same procedure was done for the annulus as well.

Blurred Semi-Realistic condition

In the Blurred Semi-Realistic (Gaussian) condition depicted in Figure 6, a Gaussian filter was used to blur the stimuli of the Semi-Realistic condition, resulting in the living room appearing less realistic compared to the Semi-Realistic and Physically Realistic conditions.

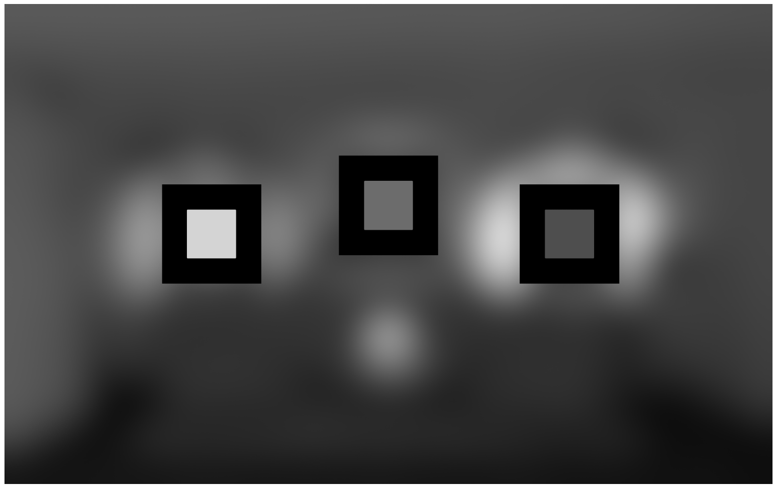


Figure 6: Example of a stimulus in the Gaussian condition.

Uniform condition

In the Uniform condition, the living room was entirely replaced with a uniform background of the same grey value. The grey value was determined by calculating the mean of each pixel value of the three squares and their annulus. Figure 7 shows an example of a stimulus in the Uniform condition.

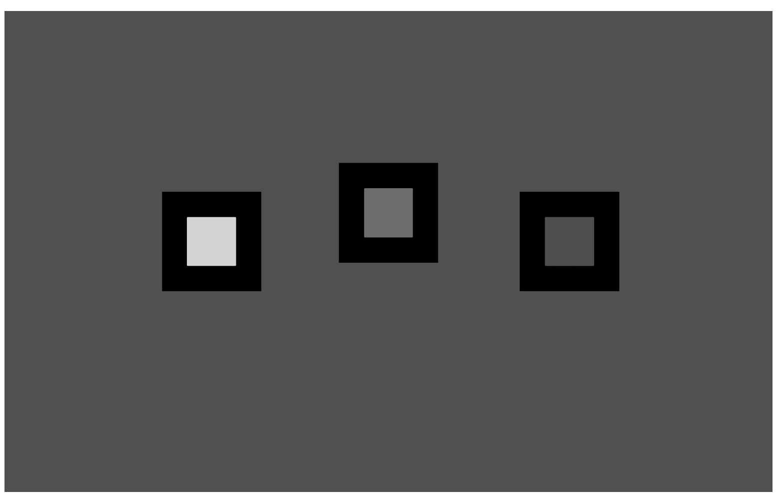
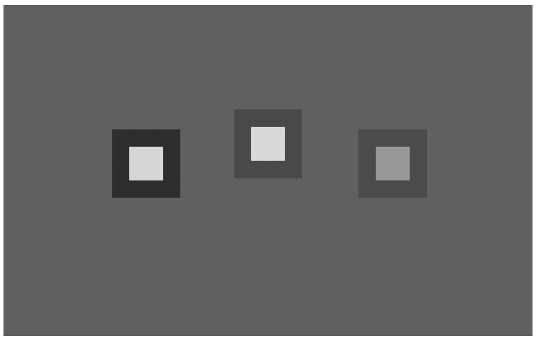


Figure 7: Example of a stimulus in the Uniform condition.

Simultaneous Contrast condition

The annulus in all the previously mentioned conditions always had a reflectance of 0%. The Simultaneous Contrast condition additionally changed the annulus reflectance to 2%

for the Uniform and Physically Realistic conditions. In the Physically Realistic condition, the annulus with 2% reflectance contained a lighting gradient. In the Uniform condition, the annulus with 2% reflectance was calculated using the mean grey pixel value. Figure 8 displays examples of stimuli in the Uniform and Physically Realistic conditions when the surround reflectance was 2%.



(a) Uniform stimulus

(b) Physically Realistic stimulus

Figure 8: Example stimuli for the Simultaneous Contrast condition with surround reflectance of 2%.

2.2 Apparatus

The experiment was conducted using PsychoPy by Peirce et al. (2019) and Python version 3.8 was used to implement the experiment. A 22-inch LCD-VIEWPixx Monitor was used to display the stimuli. The monitor had a screen resolution of 1920 x 1200 pixels and a refresh rate of 120Hz. The luminance range of the monitor was from 0.39 $\frac{cd}{m^2}$ to 245.30$\frac{cd}{m^2}$. Instead of using a power function, the ViewPixx monitor was calibrated for linear luminance using a linear-interpolation approach. The calibration details are available in the appendix. The viewing distance between the observers and the monitor was 138cm, and the viewing angle of the stimuli was 2.09°. A ResponsePixx button box with five buttons was used to measure the responses of the observers (VPixx Technologies, Inc.). The left green button was used to answer left, and the right red button was used to answer right. The red and green buttons were illuminated, and the other three buttons remained unlit.

2.3 Observers

The experiment included eight observers, out of which two were informed about the experiment (observers 1 and 2), and the remaining six observers were naïve about the purpose of the study. The observers were undergraduate students of the author's course at the University of Tübingen, and they consisted of five males and three females aged between 20 to 30 years old. Seven of the observers were right-handed, and one was left-handed, and all of them had normal or corrected-to-normal vision, which was tested using the Snellen Chart before the experiment began. All the observers, except the author, were compensated with either 15 euros per hour and received a bonus of 10 euros for every session they completed, or alternatively received course credits.

2.4 Experimental Procedure

The experiment began with the observers filling out a consent form and taking a Snellen Chart test to assess their normal or corrected-to-normal vision, with all observers scoring 20/30 or higher. The experiment consisted of two tasks: the lightness task and the brightness task, which were explained in detail in several iterations to the observers before they began the experimental conditions. In the lightness task, observers were asked the question *"Which material of the left or right square looks more similar to the material of the square in the middle?"*. In the brightness task, observers were asked the question *"Which square looks more similar to the square in the middle?"*. The following section describes the training procedure of observers before the experiment began.

Training procedure

The first training iteration involved the experimenter showing a stimulus of a middle grey piece of paper with three squares and a black annulus surrounding each square, which simulated a stimulus in the Uniform condition. The left square was perceptually white, and the middle and right squares had the same middle grey color. This stimulus can be viewed in the appendix. Observers were informed that the correct answer in the lightness task would be the right square since it was made of the same colored material as the square in the middle. The experimenter then illuminated the square in the middle with a torch to make it appear more similar to the square on the left, and observers were told that the correct answer in the lightness task would still be the right square since it was made of the same material as the square in the middle. When the observers performed the brightness task, they were shown the same stimulus again and told that the correct answer would be the left square when the middle square was illuminated by a torch since they now perceptually looked more similar in luminance.

After this explanation, observers received a printed-out briefing summarizing the task they had to perform for the experiment. The briefing was handed out separately for the lightness and brightness task. The briefing for the brightness task was only given out when the observer's next experimental condition included the brightness task. Both briefings can be found in the appendix.

The third training iteration involved observers performing 42 training trials on the monitor in the laboratory. Contrary to the first and second training iteration, which were only shown once or with the introduction of the brightness task, these training trials were performed at the beginning of every experimental condition. In the lightness task, 42 training trials were shown where one square on the left or right differed by at most 1 reflectance level compared to the middle square, and the other square differed by at least 4 reflectance levels. In the brightness task, the grey value of either the left or right square differed by at most 0.1 and the other square differed by at least 0.5. Observers received auditory feedback of 880Hz if their answer was correct (i.e., they chose the square with the closer reflectance level in the lightness task or the closer grey value in the brightness task). It was ensured that the training trials could be answered with a 100% correct rate. Throughout all the training iterations, the experimenter provided guidance and answered any questions about the real-life stimulus, the task briefings, or the training trials.

Experimental procedure

Following the instruction phase, the actual experiment began, with each stimulus being displayed for a maximum of 4.5 seconds. The opacity of the stimulus being shown was changed every 1000ms for 500ms. During these 500ms, the opacity was altered from 100% to 0% in the first 250ms and from 0% to 100% in the remaining 250ms. An inter-trial stimulus of 200ms was presented between stimuli, which consisted of a uniform grey screen. As soon as the observer responded with the left or right button on the button box the current showing of the stimulus was stopped and the inter-trial stimulus was started. If the observer did not respond within 4.5 seconds, an auditory feedback of 220 Hz was played for 100ms, and the inter-trial stimulus began, indicating that no answer was given, and the next stimulus was shown. Unlike the training trials, the observers did not receive auditory feedback when they input an answer during the experiment. Each experimental condition had the same 600 stimuli randomly sampled from a total of 2730 stimuli. These 600 stimuli were shown in a random order in every experimental condition. One experimental condition was divided into eight blocks, with each block containing 75 stimuli. Figure 9 depicts a schematic of one trial during the experiment.

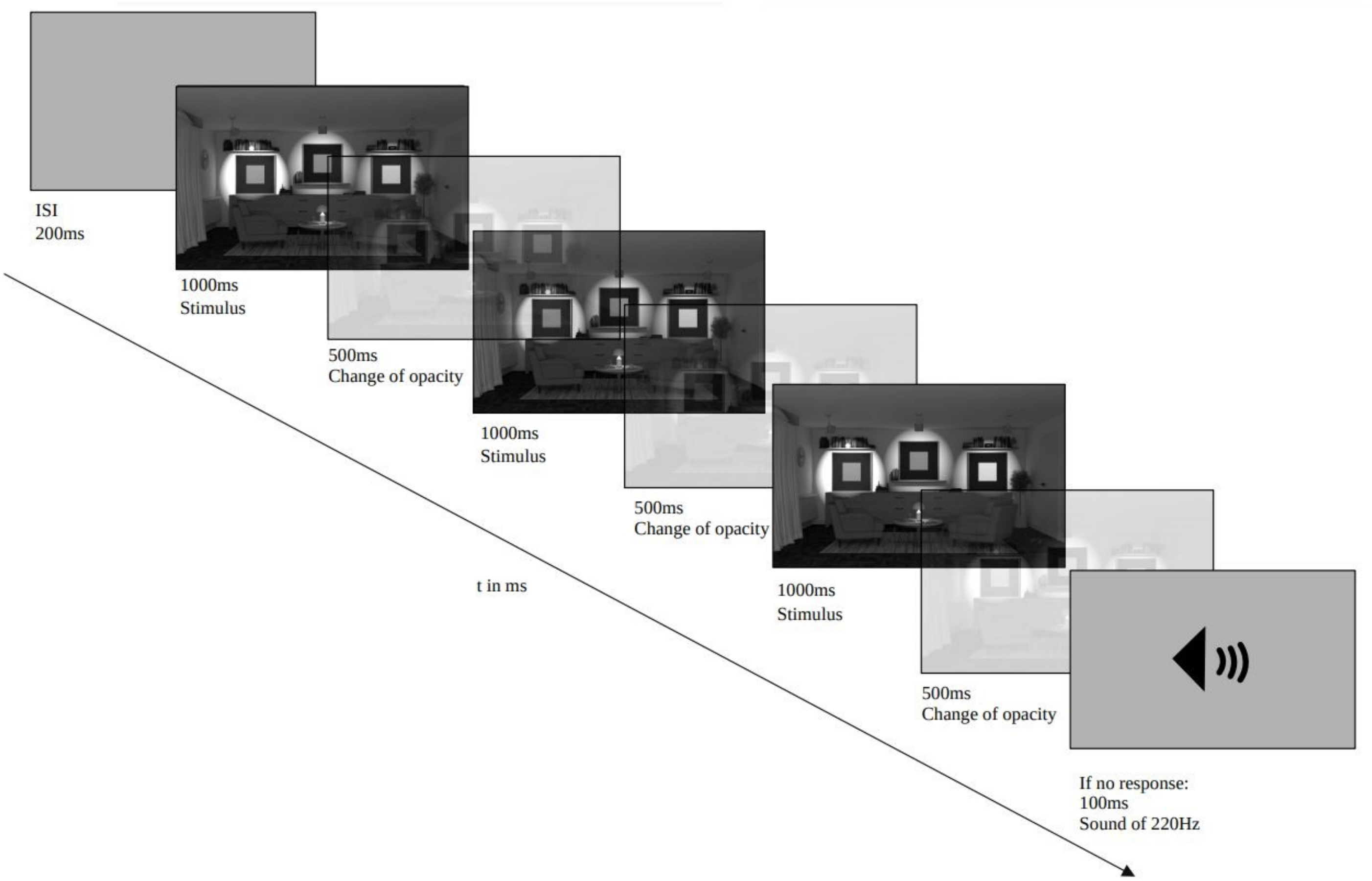


Figure 9: Schematic overview of the experimental procedure for one trial in the Physically Realistic condition.

During the blocks, the observers could take breaks. One session typically lasted around 35-50 minutes. The order of the experimental conditions and which conditions each observer completed can be seen in Table 2.

Table 2: Overview of which sessions and which order each observer participated in. U stands for Uniform, PR for Physically Realistic, and SR for Semi-Realistic conditions. L and B represent the lightness and brightness tasks. The numbers 1 and 2 indicate if the surround reflectance of the annulus was either 0% or 2% respectively.

Session	**Observers 1-4**	**Observers 5-8**
1	UL1	UL1
2	UL2	UL2
3	UB1	Gaussian
4	UB2	SRL1
5	Gaussian	PRL1
6	SRL1	PRL2
7	PRL1	
8	PRL2	
9	PRB1	
10	PRB2	

To prevent observers from forming a lightness model (i.e., remembering the illumination from the lamps in realistic conditions and subconsciously inferring them in the unrealistic conditions) the order always went from the least realistic condition to the most realistic condition. Observers completed either two experimental conditions in one session with a 15-minute break in between or three to four experimental conditions with a 40-minute break between the second and third experiment conditions in one session. After each condition, observers filled out a short questionnaire with questions about their strategy, task difficulty, and anything in the experiment that caught their attention. The questionnaire can be found in the appendix.

2.5 Data Analysis

All data, except the training trials, were used for the data analysis. Observers 1 and 2 had only 500 of the 600 trials collected in the Uniform condition lightness task. Data analysis was completed in Python (version 3.8). The data was analyzed using multidimensional scaling techniques such as the soft ordinal embedding algorithm.

Ordinal embedding algorithms are a type of machine learning method that embeds objects such as triplets into a d-dimensional space while preserving the order of the objects (Terada & Luxburg, 2014).

In our case we have sets of triplets (i, j, k) with the constraint: "*Is* x_i *more similar to* x_j *than* x_k?" (Barsukov, 2022). Responses from observers were mapped to "left" or "right" based on whether they chose x_i or x_k respectively. Two-dimensional embeddings were used for the two perceptual dimensions, which allowed the perceived difference between two stimuli to be inferred by viewing their Euclidean distance in the embedding (Terada & Luxburg, 2014). The soft ordinal embedding algorithm was implemented with the package *cblearn*. Using the *scipy* (version 1.10.0) package, all ordinal embeddings were transformed into a normalized fit using Procrustes analysis, so that comparing two different embeddings was made possible. Dissimilarity matrices were also used to represent Euclidean distances between data points of two conditions.

Triplet accuracies were used as an additional metric in the analysis, representing the proportion of triplets between two conditions in which an observer had the same response. High triplet accuracies indicate that a given observer perceived the stimuli between two conditions similarly, while low triplet accuracies indicate a difference in perception of stimuli between the two conditions. All plots were created with the packages *seaborn* (version 0.12.2), *matplotlib* (version 3.4.2), *pandas* (version 1.2.4) and *numpy* (version 1.23.5).

3 Results

3.1 Realistic vs unrealistic scenes: impact on lightness and brightness judgments

To investigate whether lightness and brightness were differently perceived in the Uniform and Physically Realistic conditions, ordinal embeddings of observer 1 were created for both conditions. The aim was to examine if the data points followed the pattern observed by Logvinenko and Maloney (2006), where data points with the same reflectance are in the same radii and data points with the same illumination are in the same concentric arcs.

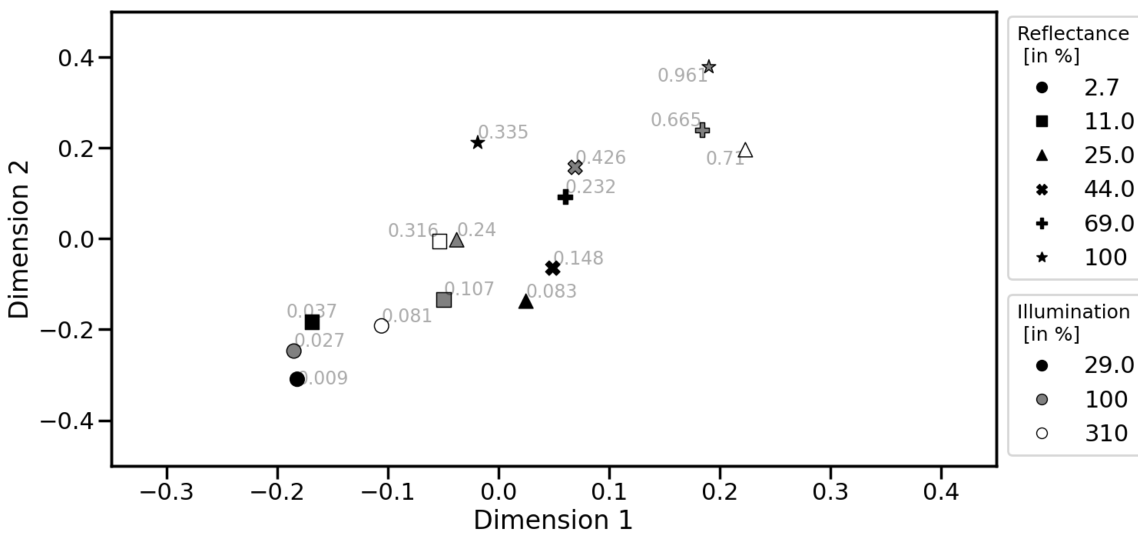


Figure 10: Ordinal embedding for the lightness task of observer 1 in the Physically Realistic condition with surround reflectance of 0%. The data points are annotated with corresponding grey values, while markers indicate reflectance levels and colors represent illumination levels.

In Figure 10 one can see that generally, data points with the same illumination are found along the same concentric arcs, but those with the same reflectance are not always in the same radii. For instance, data points with grey values of 0.24 and 0.71, despite having the same reflectance, are far apart, suggesting they were ordered more by their luminance than reflectance. On the other hand, data points with reflectance levels of 2.7% and 44% are arranged closer to each other by their reflectance values.

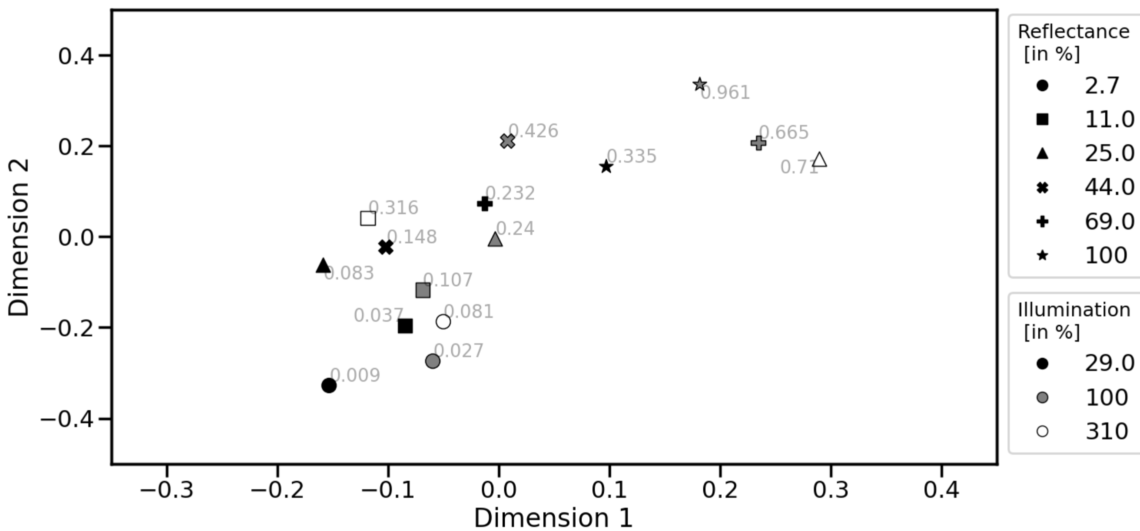


Figure 11: Ordinal embedding for the brightness task of observer 1 in the Physically Realistic condition with surround reflectance of 0%. The data points are annotated with corresponding grey values, while markers indicate reflectance levels and colors represent illumination levels.

Figure 11 demonstrates that in the brightness task for the Physically Realistic condition, distances between data points are more determined by their grey values compared to the lightness task. In comparison to Figure 10, data points with reflectances of 2.7% are further apart, and grey values of 0.232 and 0.24 are much closer together. However, contrary to expectations, the grey value 0.655 is closer to 0.961 than 0.71, and 0.335 is closer to 0.961 than 0.426, which may suggest these were perceived more similarly by reflectance values than grey values.

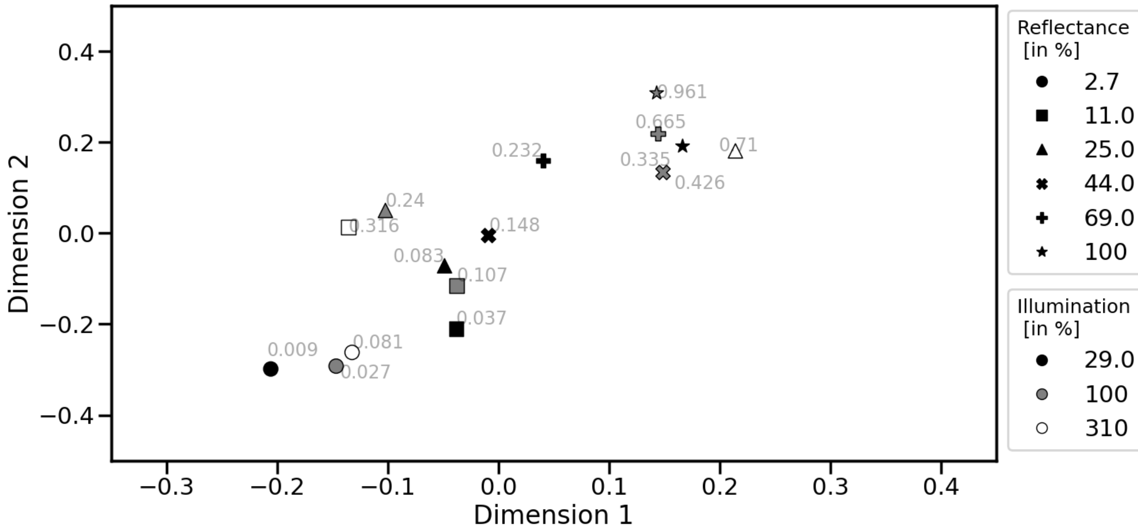


Figure 12: Ordinal embedding for the lightness task of observer 1 in the Physically Realistic condition with surround reflectance of 2%. The data points are annotated with corresponding grey values, while markers indicate reflectance levels and colors represent illumination levels.

Figure 12 displays the embedding for the lightness task with a surround reflectance of 2%. Data points with the same reflectances, such as 2.7% and 100%, lie closer to each other than in the lightness task with a surround reflectance of 0%. Many data points that are close together have large differences in grey values, such as 0.961, 0.665, 0.335, and 0.71, indicating that these were perceived more similarly because of similar reflectance values.

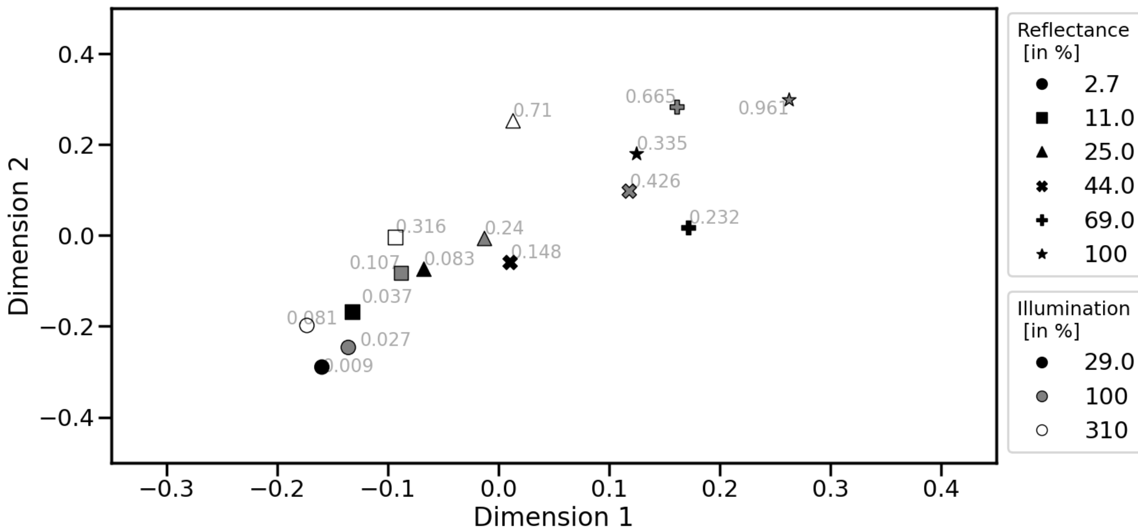


Figure 13: Ordinal embedding for the brightness task of observer 1 in the Physically Realistic condition with surround reflectance of 2%. The data points are annotated with corresponding grey values, while markers indicate reflectance levels and colors represent illumination levels.

Figure 13 shows that the data points are now perceived more similarly based on their grey value compared to the lightness condition. Despite this, some data points still appear to be closer to each other based on reflectance. For instance, the data points with grey values of 0.24 and 0.232 are found far apart, and data points with grey values of 0.335 and 0.665 are closer to the highest grey value of 0.961 than 0.71.

The subsequent two figures depict the triplet accuracies for the lightness and brightness tasks for the two different surround reflectances to investigate if triplet accuracy is lower in the Physically Realistic condition.

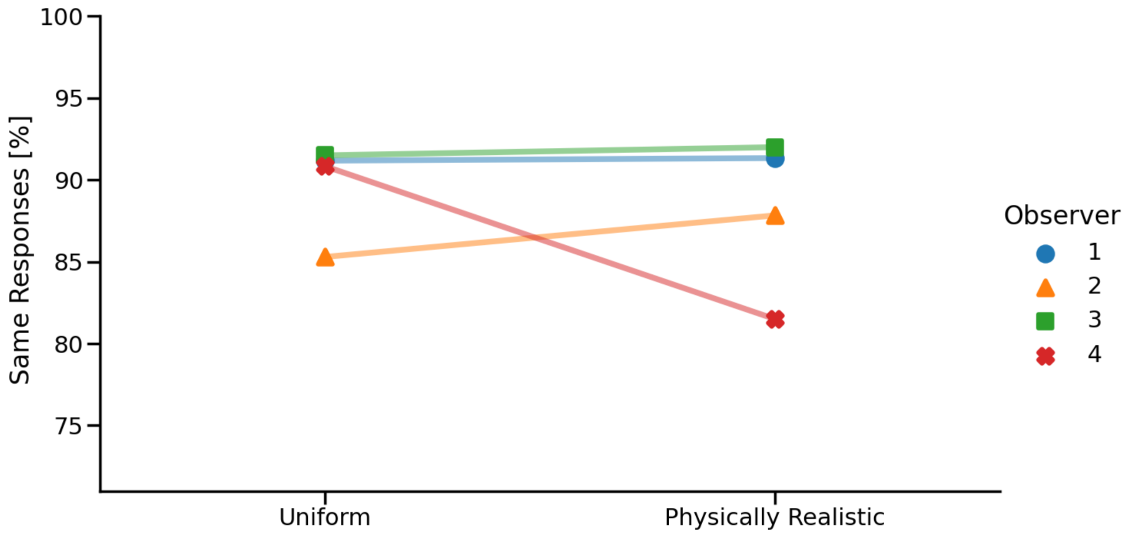


Figure 14: Triplet accuracy for every observer: On the left side, data points show the proportion of the same responses to triplets in the Uniform condition between lightness and brightness tasks. On the right side, data points show the proportion of the same responses to triplets in the Physically Realistic condition between lightness and brightness tasks. The surround reflectance in both conditions was 0%.

Figure 14 displays the triplet accuracy between the lightness and brightness tasks with a 0% surround reflectance. Observers 1 and 3 show a high triplet accuracy in both the Uniform and Physically Realistic conditions, indicating that they either cannot distinguish between the lightness and brightness task or used a similar strategy in responding to triplets in the different tasks. Observer 4 has a high triplet accuracy in the Uniform condition but a low triplet accuracy in the Physically Realistic condition, which suggests that this observer can differentiate between lightness and brightness in the more realistic condition. Observer 2 has a low triplet accuracy in the Uniform condition but a higher triplet accuracy in the Physically Realistic condition.

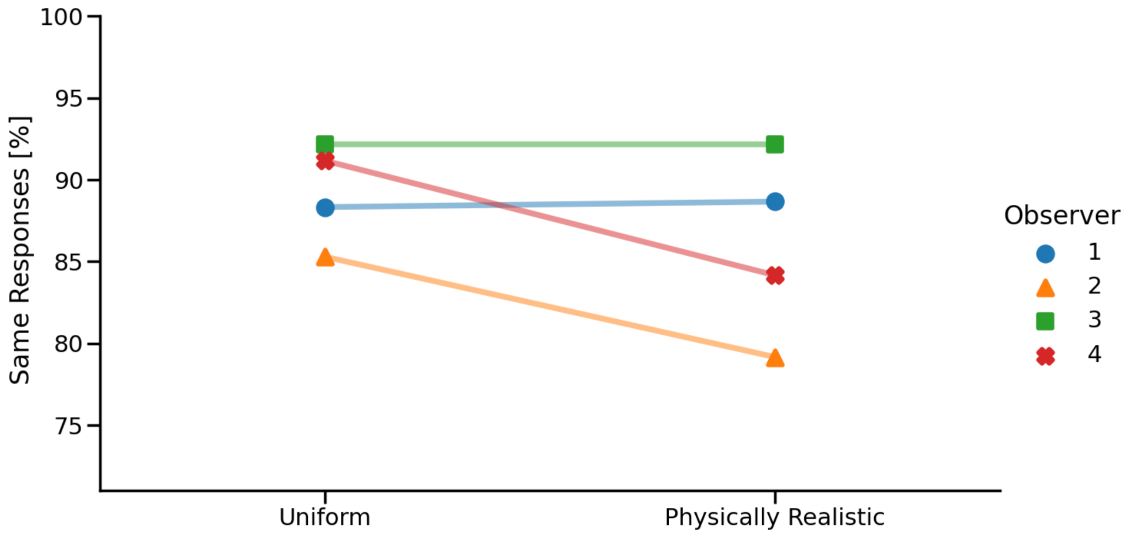


Figure 15: Triplet accuracy for every observer: Data points on the left show proportion of the same responses to triplets of the lightness and brightness task in the Uniform condition. Data points on the right the proportion of the same responses to triplets of the lightness and brightness task in the Physically Realistic condition. Surround reflectance was 2%.

Figure 15 shows the triplet accuracy between the lightness and brightness tasks when the surround reflectance was 2%. Observers 1 and 3 have high triplet accuracy in both conditions, similar to the 0% surround reflectance condition. Observers 2 and 4 exhibit high triplet accuracy in the Uniform condition and lower triplet accuracy in the Physically Realistic condition, suggesting that they could differentiate between lightness and brightness in the Physically Realistic condition.

3.2 The effect of task instructions

To investigate if task instructions have an impact on observer responses, this section will present the triplet accuracy and dissimilarity matrices for the lightness and brightness tasks in the Uniform condition.

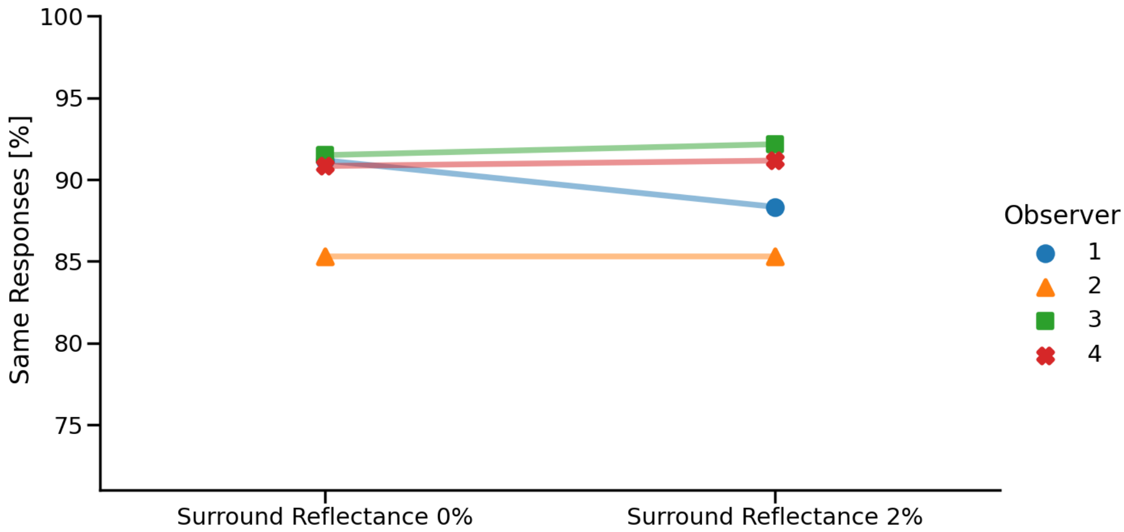


Figure 16: Triplet accuracy for every observer: Data points on the left show proportion of the same responses to triplets of the lightness and brightness task in the Uniform condition with the surround reflectance of 0%. Data points on the right the proportion of the same responses to triplets of the lightness and brightness task in the Uniform condition with the surround reflectance of 0%.

Figure 16 displays the triplet accuracy between the lightness and brightness tasks for each observer in the Uniform condition with surround reflectance of 0% and 2%. All observers, except for observer 1, show similar triplet accuracy in both conditions. Observer 1 appears to have slightly different judgments between lightness and brightness tasks when the surround reflectance is 2%. Observer 2 has a lower triplet accuracy in both surround reflectance conditions compared to the other observers, indicating that this observer may have responded differently to triplets in the lightness and brightness tasks.

The following two figures present dissimilarity matrices to examine potential differences in the lightness and brightness tasks for observer 1. If the tasks are similar, the values on the diagonal should be low and the values on either side of the diagonal should mirror each other.

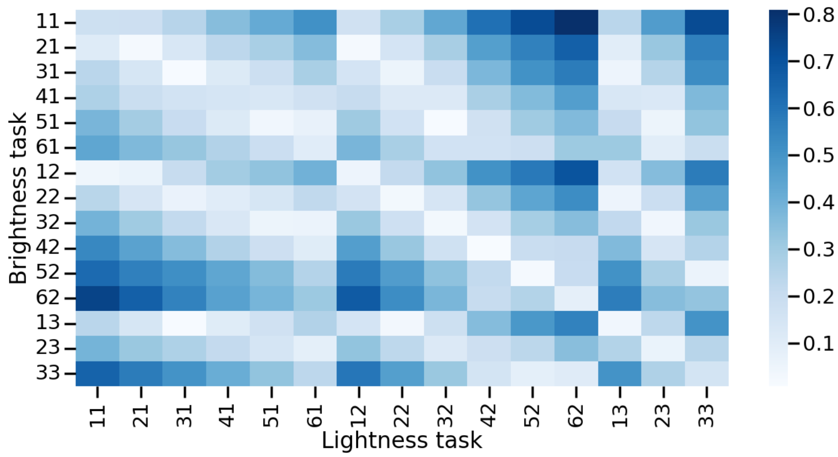


Figure 17: Dissimilarity matrix of observer 1 between the lightness and brightness tasks in the Uniform condition with a surround reflectance of 0% The numbers on the x-axis represent indices of reflectance and illumination values of data points in an embedding in ascending order, and the same for the y-axis.

Figure 17 shows a dissimilarity matrix for observer 1 between the lightness and brightness tasks in the Uniform condition. The responses to the lightness and brightness task in the Uniform condition with surround reflectance of 0% are very similar. Values on the diagonal have low dissimilarity and the dissimilarities are mirrored left and right from the diagonal, suggesting that there is no or little difference in triplet responses.

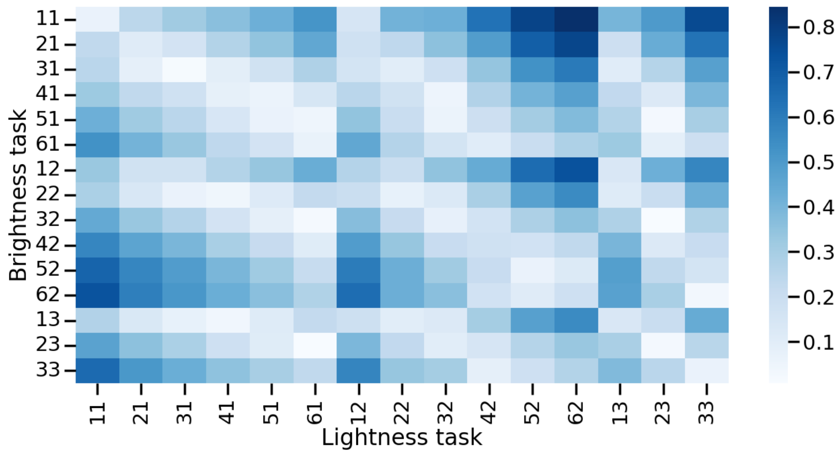


Figure 18: Dissimilarity matrix of observer 1 between the lightness and brightness tasks in the Uniform condition with a surround reflectance of 2% The numbers on the x-axis represent indices of reflectance and illumination values of data points in an embedding in ascending order, and the same for the y-axis.

Figure 18 shows that observer 1's responses to the lightness and brightness task in the Uniform condition with surround reflectance of 2% are very similar to Figure 17. However, the dissimilarity values for points 11 and 62 have larger heat on the right side of the diagonal than on the left side.

3.3 Degrees of realism

For the different degrees of realism of the stimuli, first, the vector differences between two conditions are shown, then the triplet accuracy for the different degrees of realism is shown.

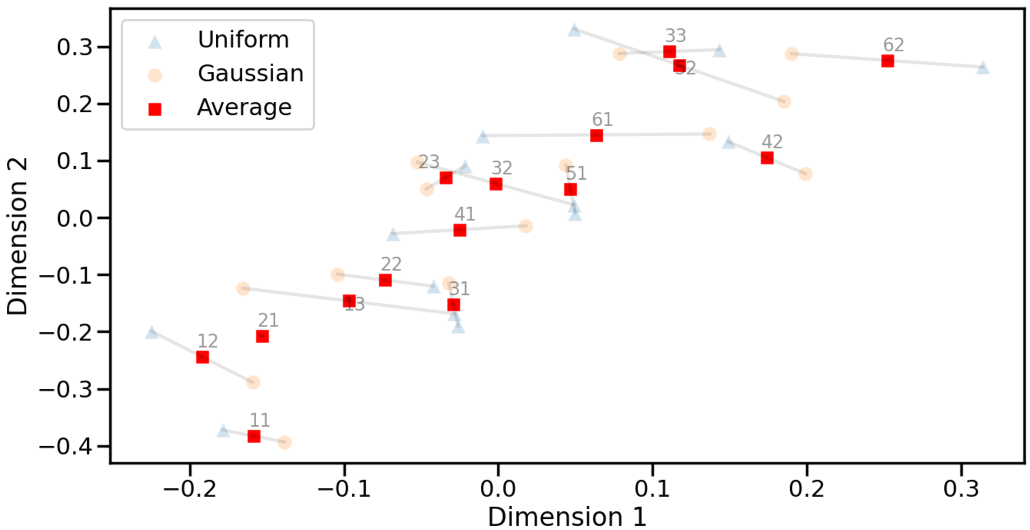


Figure 19: Vector differences of the lightness task between Uniform and Gaussian conditions with surround reflectance of 0%. The Average data points show the mean coordinates of data values with the same reflectance and illumination of the two conditions. The two numbers in the annotation of the data points represent the indices of the reflectance and illumination values in ascending order respectively.

Figure 19 displays the vector differences of the lightness task between the Uniform and Gaussian conditions with surround reflectance of 0%. The data points with the same reflectance values are closer together in the Gaussian condition than in the Uniform condition. Particularly, data points 61 and 62 with a reflectance of 100%, and data points 11, 12, and 13 with a reflectance of 2.7% are much closer together in the Gaussian condition. Data points in the Uniform condition appear to be perceived more similarly by their grey values, which is evident from data points 11 and 62 with the lowest and highest grey values being further apart in the Uniform condition than in the Gaussian condition.

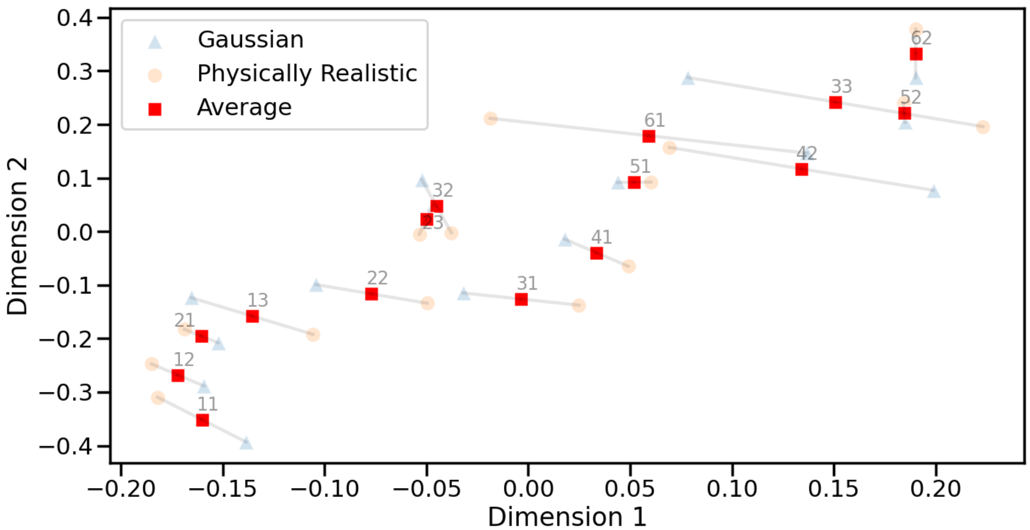


Figure 20: Vector differences of the lightness task between Gaussian and Physically Realistic conditions with surround reflectance of 0%. The Average data points show the mean coordinates of data values with the same reflectance and illumination of the two conditions. The two numbers in the annotation of the data points represent the indices of the reflectance and illumination values in ascending order respectively.

Figure 20 displays the vector differences between the Gaussian and Physically Realistic conditions of observer 1. There is a trend in both conditions that data points with the same reflectance are perceived more similarly. Most data points do not show a large difference in perception between conditions, but some values are far apart. For instance, data points 61 and 62 are much closer together in the Gaussian condition and much further apart in the Physically Realistic condition. Conversely, data points 41 and 42 are much closer together in the Physically Realistic condition and much further apart in the Gaussian condition. This suggests that some reflectances are more easily judged by lightness in the Gaussian condition, while others are more easily judged by lightness in the Physically Realistic condition.

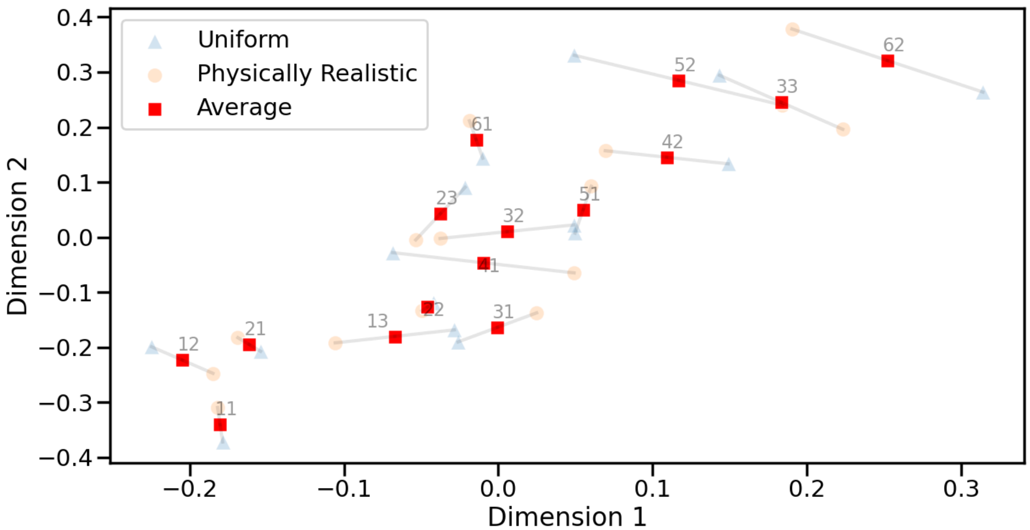


Figure 21: Vector differences of the lightness task between Uniform and Physically Realistic conditions with surround reflectance of 0%. The Average data points show the mean coordinates of data values with the same reflectance and illumination of the two conditions. The two numbers in the annotation of the data points represent the indices of the reflectance and illumination values in ascending order respectively.

Figure 21 displays the vector differences between the Uniform condition and the Physically Realistic condition of observer 1. Contrary to expectation, the differences are not much larger than between the Uniform and Gaussian condition. In the Physically Realistic condition, data points with the same reflectance are perceived as more similar than in the Uniform condition. Data points in the Uniform condition appear to be perceived more similarly by similar grey values.

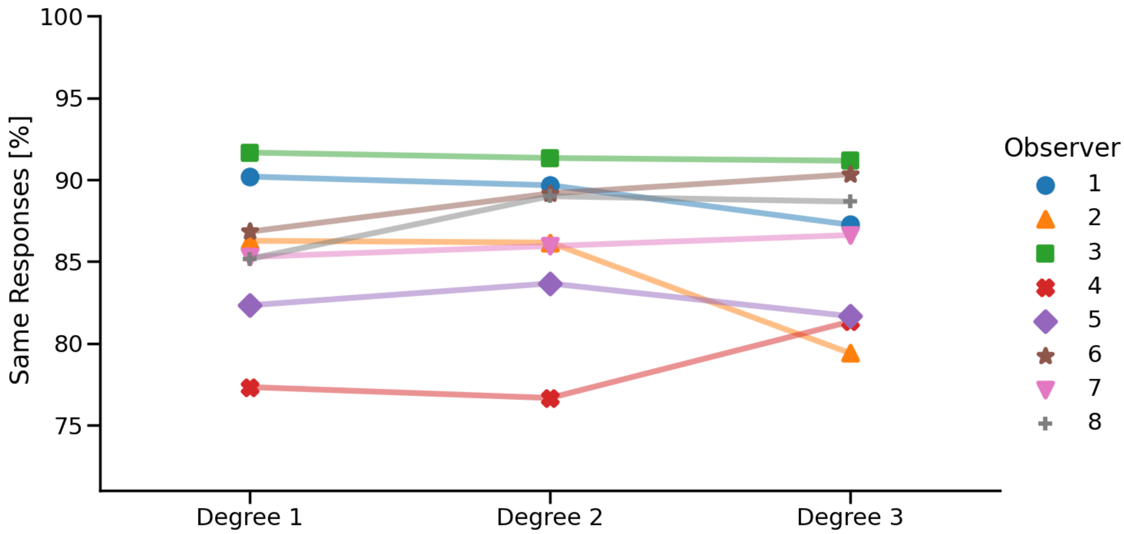


Figure 22: Triplet accuracy for every observer for the different degrees of realism in the lightness task with a surround reflectance of 0%. Degree 1 represents the triplet accuracy between the Uniform and Gaussian condition, degree 2 between the Gaussian and Physically Realistic conditions, and degree 3 between the Uniform and Physically Realistic conditions.

Figure 22 displays the triplet accuracy between each degree of realism, with degree 1 representing the Uniform and Gaussian condition, degree 2 representing the Gaussian and Physically Realistic conditions, and degree 3 representing the Uniform and Physically Realistic conditions. Contrary to what the vector differences in the previous Figures described, differences in triplet accuracy for most observers are not noteworthy and appear to be random. For example, observer 4 has a much higher triplet accuracy in degree 3, despite the expectation that triplet accuracy should decrease in this condition. For observers 1 and 3, triplet accuracy decreases with increasing degrees of realism. For observers 6, 7, and 8, triplet accuracy increases with increasing degrees of realism.

3.4 Lighting gradients within realistic scenes

The following analysis focuses on the lighting gradients in realistic scenes. Specifically, the vector differences and the dissimilarity matrix between the Semi-Realistic condition and the Physically Realistic condition are presented.

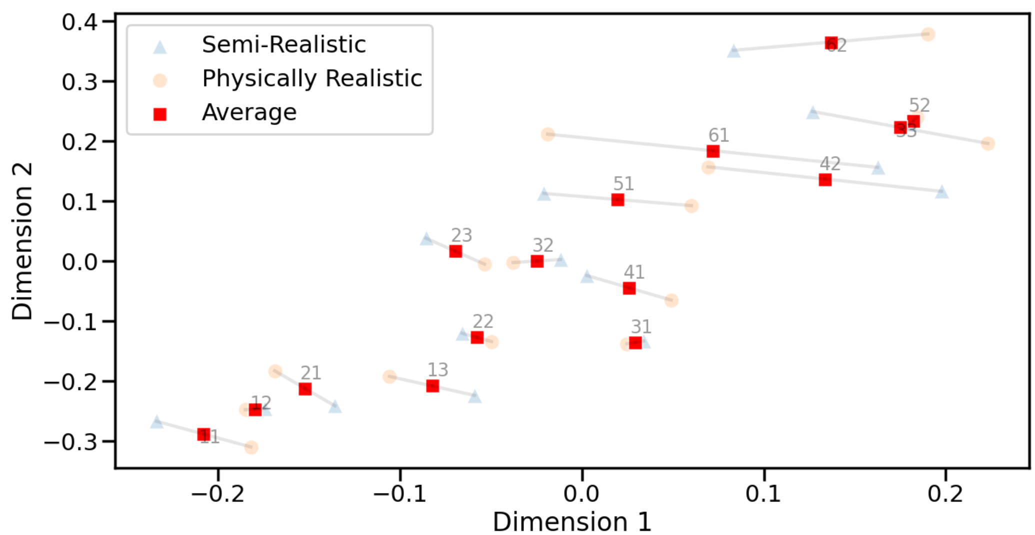


Figure 23: Vector differences of the lightness task between Semi-Realistic and Physically Realistic conditions with surround reflectance of 0%. The Average data points show the mean coordinates of data values with the same reflectance and illumination of the two conditions. The two numbers in the annotation of the data points represent the indices of the reflectance and illumination values in ascending order respectively.

In Figure 23, the vector differences between most reflectance values in the Semi-Realistic and lower reflectance values are perceived as very similar, while larger differences are observed in higher reflectance values such as 61 and 62, 51 and 52, and 33. However, it appears that lightness cannot be judged better in the Physically Realistic condition based on overall observations.

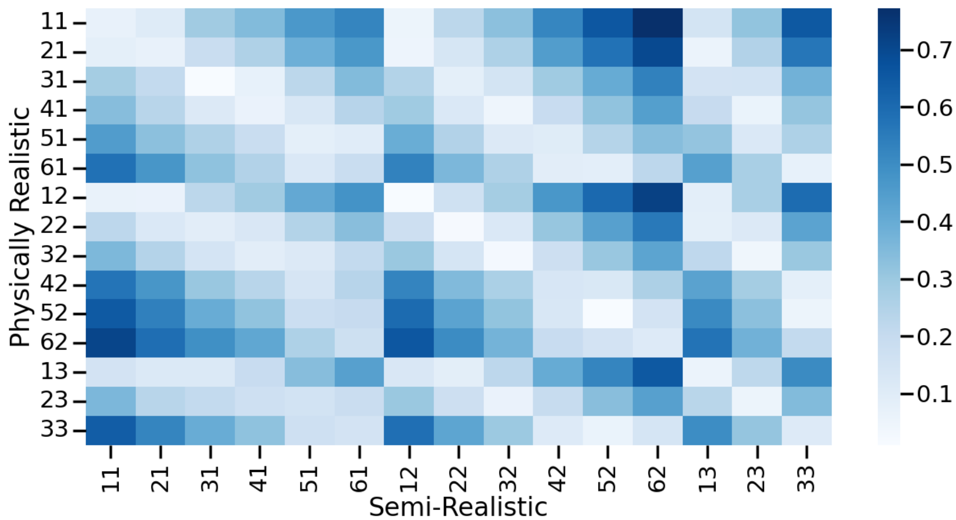


Figure 24: Dissimilarity matrix of observer 1 between the Semi-Realistic and Physically Realistic conditions with a surround reflectance of 0% The numbers on the x-axis represent indices of reflectance and illumination values of data points in an embedding in ascending order, and the same for the y-axis.

Figure 24 presents the dissimilarity matrix, which supports the vector difference results from Figure 23. The diagonal of the dissimilarity matrix reveals that data points with the same reflectance and illumination have lower Euclidean distances. The values on the right and left of the diagonal also have similar Euclidian distances. Individual data points such as 62 and 11 have slightly higher Euclidian distances in the Physically Realistic condition than in the Semi-Realistic condition.

3.5 Simultaneous contrast effect in realistic scenes

This section will serve to show if the simultaneous contrast effect can influence lightness and brightness judgment in Uniform and Physically Realistic conditions. First, the vector differences are presented, and then the triplet accuracies for both conditions.

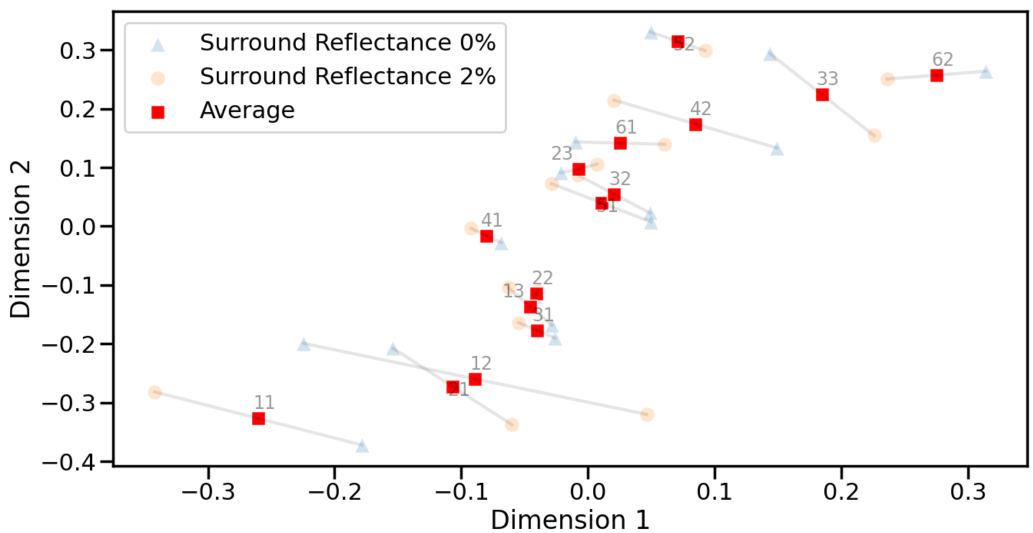


Figure 25: Vector differences of the lightness task in the Uniform condition with surround reflectances of 0% and 2%. The Average data points show the mean coordinates of data values with the same reflectance and illumination of the two conditions. The two numbers in the annotation of the data points represent the indices of the reflectance and illumination values in ascending order respectively.

The vector differences in Figure 25 show that in the Uniform condition, data points with similar grey values are arranged closer to each other than those with similar reflectances, for both the 0% and 2% surround reflectance conditions. The majority of data points are perceived similarly in both conditions, but those with low reflectance values (such as 11, 12, and 21) have a larger vector difference.

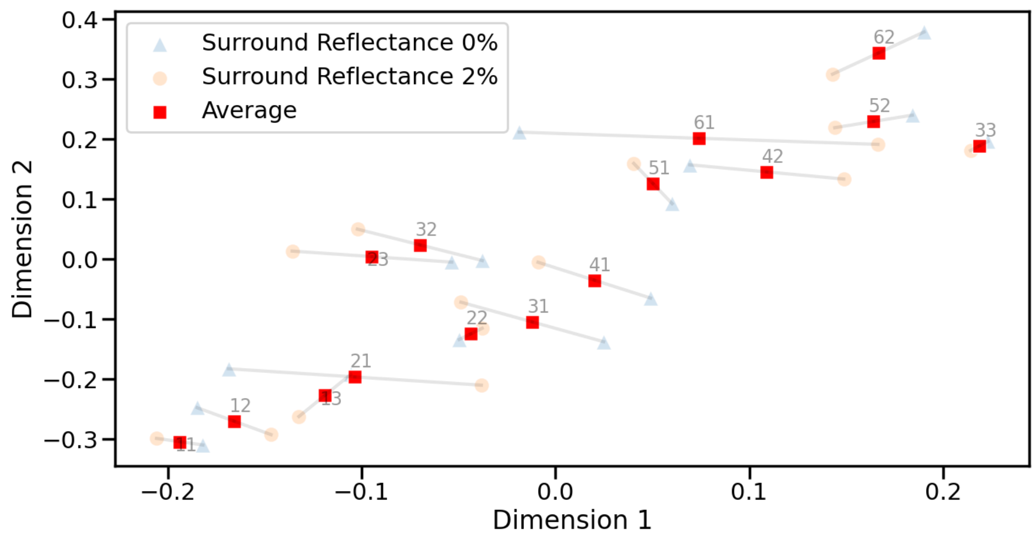


Figure 26: Vector differences of the lightness task in the Physically Realistic condition with surround reflectances of 0% and 2%. The Average data points show the mean coordinates of data values with the same reflectance and illumination of the two conditions. The two numbers in the annotation of the data points represent the indices of the reflectance and illumination values in ascending order respectively.

Figure 26 shows that in the Physically Realistic condition, data points with similar reflectance values are arranged closer to each other than data points with similar grey values, regardless of the surround reflectance condition. Compared to the Uniform condition, most data points in the Physically Realistic condition have larger vector differences. Some reflectances such as 61 and 62 lie much closer to each other when surround reflectance is 2% than when it is 0%. The differences in radii between some reflectance values, such as 11, 12, 13 and 21, 22, 23 and 31, 32, 33, differ greatly between the two surround reflectance conditions.

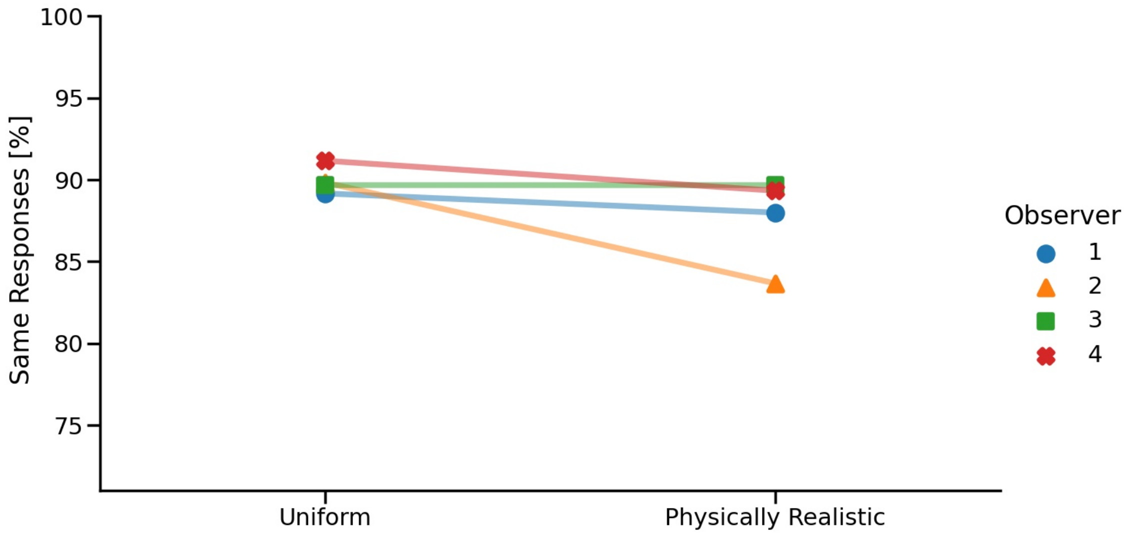


Figure 27: Triplet accuracy for every observer in the brightness task: Data points on the left show proportion of the same responses to triplets in the Uniform condition for the two surround reflectances of 0% and 2%. Data points on the right show proportion of the same responses to triplets in the Physically Realistic condition for the two surround reflectances of 0% and 2%.

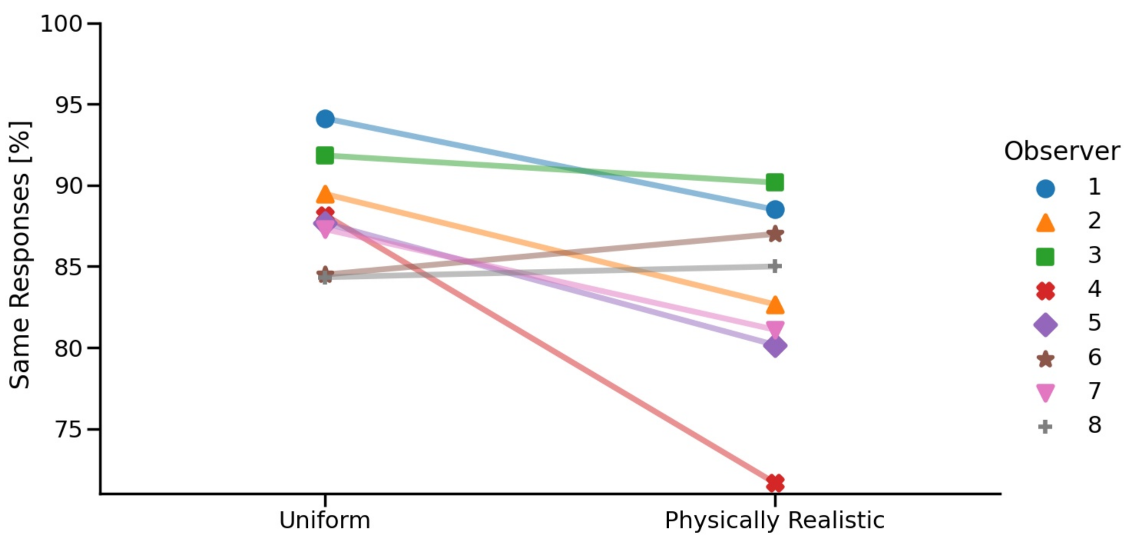


Figure 28: Triplet accuracy for every observer in the lightness task: Data points on the left show proportion of the same responses to triplets in the Uniform condition for the two surround reflectances of 0% and 2%. Data points on the right show proportion of the same responses to triplets in the Physically Realistic condition for the two surround reflectances of 0% and 2%.

Figures 27 and 28 show the results of the triplet accuracy for the influence of the surround reflectance in the lightness and brightness tasks, respectively. For all observers, except 6 and 8, triplet accuracy drops in the Physically Realistic condition in both tasks. The largest drop is seen in observer 3. Observers 6 and 8 have lower triplet accuracy in the Uniform condition as well, suggesting that the simultaneous contrast may have affected them in both conditions. The results of Figures 27 and 28 are consistent with the vector differences, indicating that data points are perceived differently in the Physically Realistic condition compared to the Uniform condition.

4 Discussion

In this work, we used 3D photo-realistic scenes to investigate whether the human visual system uses realism as a cue for judging lightness and brightness. The scenes were varied in different ways to investigate different factors of realism. This section will discuss the results of the experiments, as well as potential areas of improvement and future studies.

The results of our analysis on ordinal embeddings in the lightness task and brightness task partially replicated the findings of Logvinenko and Maloney (2006). Vector differences between lightness and brightness tasks showed that stimuli with the same reflectance were closer in the lightness task than in the brightness task. However, the structure of the scaling in the lightness task was not as distinct as the scaling in the study by Logvinenko and Maloney (2006). One explanation for this discrepancy is that the distinct ordering of reflectances in the same radii and illumination in the same arcs may have been an artifact of the multidimensional scaling method used in that study. Another possible explanation is that observers in our study may not have always performed the lightness task correctly. It is evident from the answers in the questionnaire that were filled in after every session, that many observers did indeed understand the task at hand, but nonetheless often judged squares by their similarity in grey value and not in the material (i.e., their reflectance). The triplet accuracies do not seem to confirm the results of the vector differences. Here, observers are shown to have a difference in the judgment of lightness and brightness according to the vector differences but not in the triplet accuracy. Both Uniform and Physically Realistic conditions showed high triplet accuracy, indicating difficulty in differentiating between lightness and brightness. However, triplet accuracy may not be informative enough to rule out any effects of the lightness and brightness tasks. The abundance of easy stimuli, such as triplets with similar grey values (e.g., 0.009, 0.335, and 0.961), might have decreased the impact of stimuli that affect perception, leading to a small effect on the overall proportion of stimuli with the same response. In future studies, it may be beneficial to increase the number of stimuli that are similar in luminance but different in reflectance while decreasing the number of easily distinguishable stimuli.

Triplet accuracy and dissimilarity matrices showed that the perception of lightness and brightness was not affected by the different instructions in the Uniform condition. High triplet accuracy was observed for both tasks in the Uniform condition with surround reflectance of 0% and 2%. The dissimilarity matrices also suggest that there is little difference between the lightness and brightness tasks in the Uniform condition. These results suggest that observers judged stimuli based on their grey value, regardless of the instructions given. However, similar to what has been explained above, it may be the case that triplet accuracy is not informative enough again to draw a conclusion regarding the effect of different instructions on observers' responses. Future studies may benefit from investigating this question with other techniques such as using more tasks and comparing more conditions instead of only the Uniform condition.

Vector differences between the different degrees of realism indicate that there is a difference in lightness between the Uniform condition and the Gaussian condition (degree 1), and between the Gaussian condition and the Physically Realistic condition (degree 2). There is also a difference between the Uniform condition and the Physically Realistic condition (degree 3), but the difference does not seem larger than that between the other two degrees of realism. These findings suggest that the visual system can use information about the lighting of a scene, even when the context is not entirely apparent, to judge lightness. However, triplet accuracies do not seem to show any trend in better lightness judgment with increasing degrees of realism. It would be interesting to explore if other degrees of realism could impact different lightness judgments. Could it for example be possible, that the Gaussian condition was still too realistic? Further research could investigate if a stronger blurring could make a more significant difference when compared to the Physically Realistic condition.

Both vector differences and the dissimilarity matrices suggest that the lighting gradient has little or no effect on lightness judgment. It is possible that other cues in the realistic scene, besides the lighting gradient, may have been sufficient for the visual system to judge lightness accurately. Future experiments could investigate whether the gradient of stimuli affects lightness judgments when the scene is unrealistic, such as in the Uniform background condition. It would be interesting to explore whether the lighting gradient is enough to inform the visual system about the nature of lighting, even when the lamps providing illumination are not visible.

The triplet accuracies in the simultaneous contrast condition show that there is a clear trend of decreasing triplet accuracy in the Physically Realistic conditions compared to the Uniform conditions for both surround reflectances of 0% and 2%. This suggests that the visual system may use simultaneous contrast as a cue to gather information about the lighting of the scene. Since the surround reflectance was fixed to 2% in this experiment, the visual system may be able to exactly infer which of the three illuminations may be coming from the lamps and thus be more able to judge lightness. Investigating if changing the surround reflectance randomly to other percentages in the same session would yield similar results could be interesting, as the annulus would no longer always correspond to the same luminance for the same lamp illumination. Results of the vector differences also support the triplet accuracy findings, showing that data values are much further apart in the Physically Realistic condition than in the Uniform conditions.

Our results are in agreement with previous studies conducted by Maertens et al. (2015), Barsukov (2022), and Murray (2021), which indicate that apparent lightness can be influenced by the degree of realism in the stimuli. Particularly, the findings suggest that simultaneous contrast and high degrees of realism can strongly impact the judgment of lightness by the visual system. The use of multidimensional scaling techniques, such as triplets and ordinal embedding algorithms, has promise in investigating these phenomena effectively.

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6 Appendix

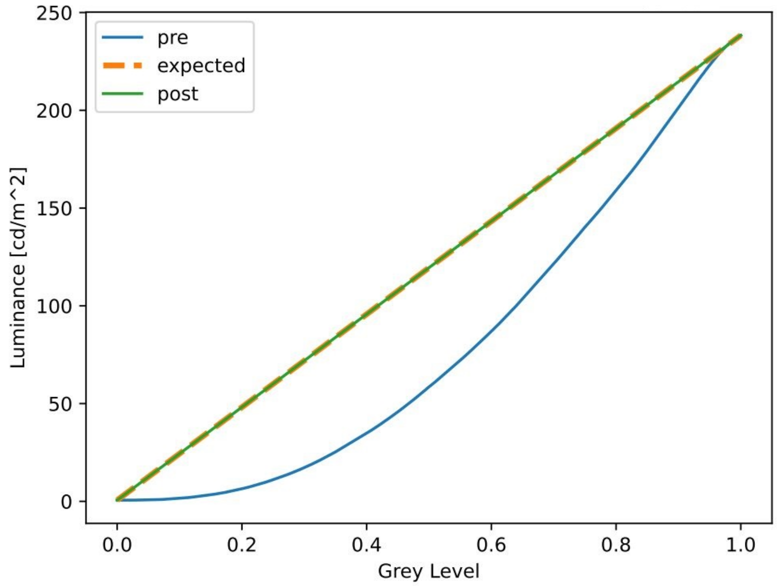


Figure 29: Luminances on the VIEWPixx monitor before and after calibration.

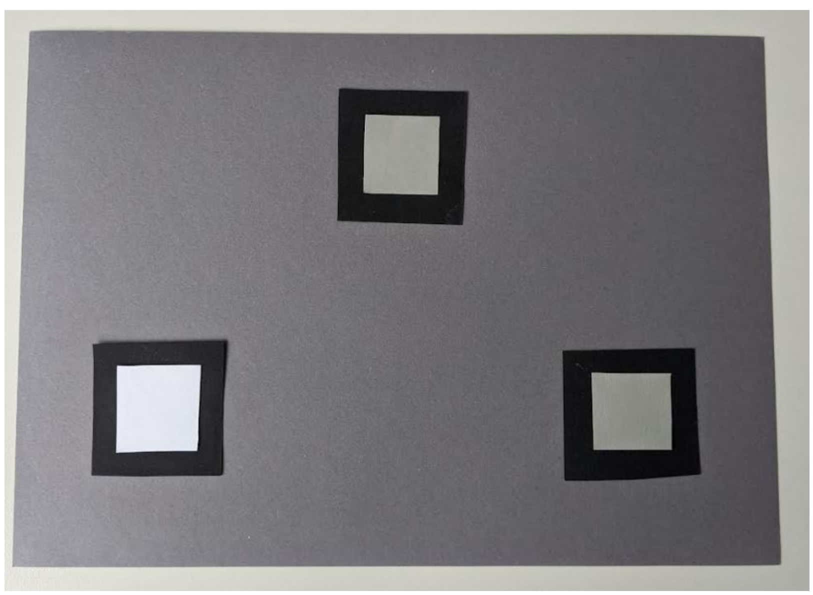
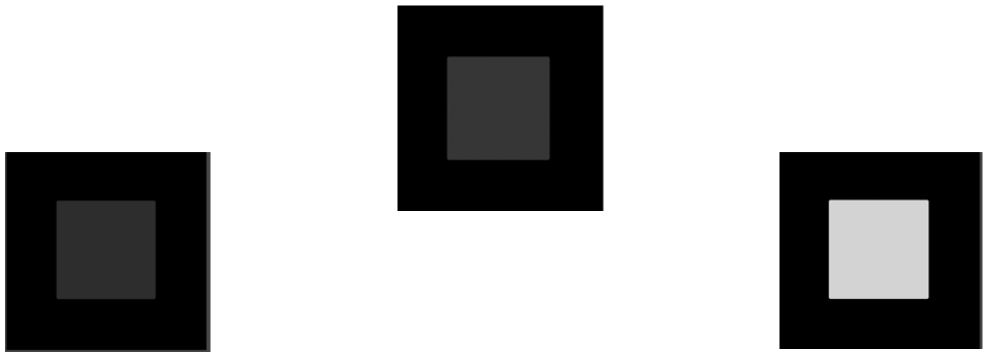


Figure 30: Real stimulus simulating the uniform condition. Used in the briefing: illuminating the middle square with a torch made it look more similar to the left square.

Briefing: Triplet Experiment

Neural Information Processing Group, 2023

In dem Experiment wirst du Stimuli dieser Art sehen:



Aufgabe A

Welches Quadrat sieht aus, als wäre es aus einem Material, das dem Material des Quadrats in der Mitte ähnlicher ist? Beachte dabei jeweils immer das *innere* (graue) Quadrat und nicht die schwarze Umrandung. Drücke den **linken Knopf** (Farbe Grün) für das linke Quadrat und den **rechten Knopf** (Farbe Rot) für das rechte Quadrat.

Du wirst am Anfang des Experiments zunächst einen Trainingsblock durchführen. Dabei erhältst du durch einen Ton Feedback, ob du richtig geantwortet hast. Ein hoher Ton bedeutet die Antwort ist richtig und ein tiefer Ton bedeutet die Antwort ist falsch.

Danach beginnt das Experiment, welches insgesamt aus sieben Blöcken mit je 72 Durchgängen besteht. Zwischen den Blöcken hast du die Möglichkeit, Pausen zu nehmen. Nutze diese, wenn du merkst, dass deine Konzentration nachlässt oder du müde wirst! Das Experiment sollte etwa 40 Minuten andauern.

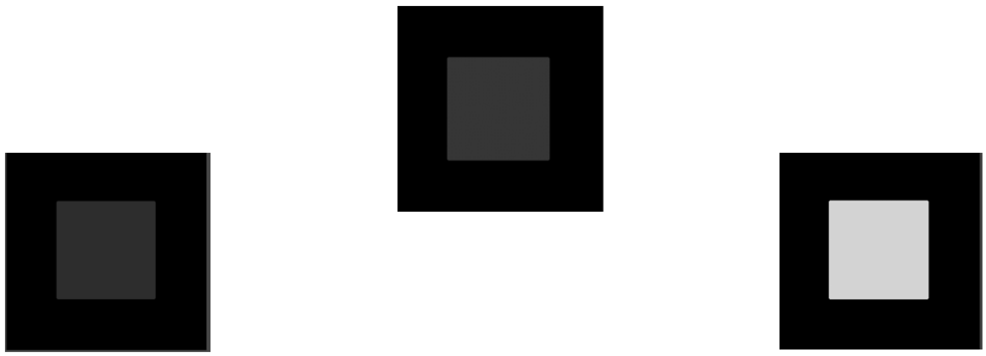
Hinweis*:* Außerhalb des Trainingsblocks gibt es keine „richtigen" oder „falschen" Antworten. Antworte wie du es für richtig hältst.

Solltest du noch Fragen haben, dann wende dich gerne an deinen Versuchsleiter. Danke für deine Teilnahme!

Briefing: Triplet Experiment

Neural Information Processing Group, 2023

In dem Experiment wirst du Stimuli dieser Art sehen:



Aufgabe B

Welches Quadrat sieht *ähnlicher* aus zu dem Quadrat in der Mitte, d.h. die Helligkeit von welchem Quadrat ist ähnlicher der Helligkeit des Quadrats in der Mitte?

Es geht in dieser Aufgabe also nur darum, die Helligkeit der Quadrate zu vergleichen, nicht mehr darum, ob die Materialien ähnlicher sind**.** Beachte dabei jeweils immer das *innere* (graue) Quadrat und nicht die schwarze Umrandung. Drücke den **linken Knopf** (Farbe Grün) für das linke Quadrat und den **rechten Knopf** (Farbe Rot) für das rechte Quadrat.

Du wirst am Anfang des Experiments zunächst einen Trainingsblock durchführen. Dabei erhältst du durch einen Ton Feedback, ob du richtig geantwortet hast. Ein hoher Ton bedeutet die Antwort ist richtig und ein tiefer Ton bedeutet die Antwort ist falsch.

Danach beginnt das Experiment, welches insgesamt aus sieben Blöcken mit je 72 Durchgängen besteht. Zwischen den Blöcken hast du die Möglichkeit, Pausen zu nehmen. Nutze diese, wenn du merkst, dass deine Konzentration nachlässt oder du müde wirst! Das Experiment sollte etwa 40 Minuten andauern.

Hinweis*:* Außerhalb des Trainingsblocks gibt es keine „richtigen“ oder „falschen“ Antworten. Antworte wie du es für richtig hältst.

Solltest du noch Fragen haben, dann wende dich gerne an deinen Versuchsleiter. Danke für deine Teilnahme!

Triplet Experiment Debriefing

Versuchsperson: X

Session: X

Wie war das Experiment?

Ist dir etwas aufgefallen? Konntest du einen Unterschied zu den vorherigen Bedingungen feststellen?

Hast du eine Strategie benutzt, wenn ja welche?

Wie fandest du die Schwierigkeit?

Ordinal embeddings of observers 2-8

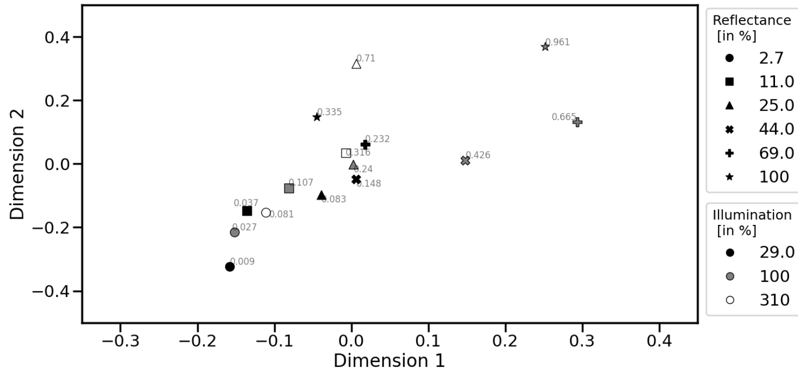


Figure 31: Ordinal embedding of observer 2 for the lightness task in the Physically Realistic condition with surround reflectance 0%.

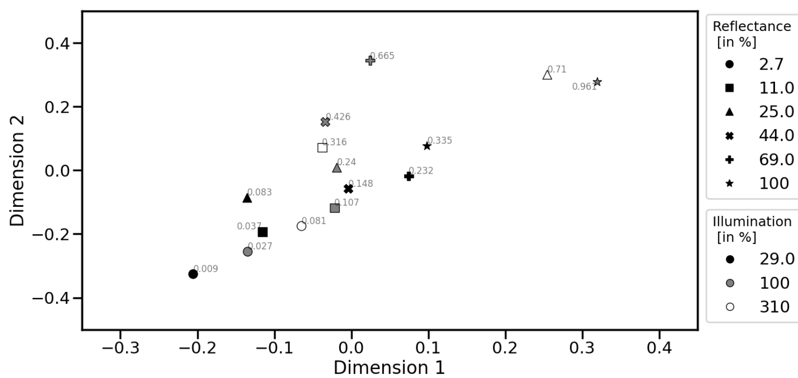


Figure 32: Ordinal embedding of observer 2 for the brightness task in the Physically Realistic condition with surround reflectance 0%.

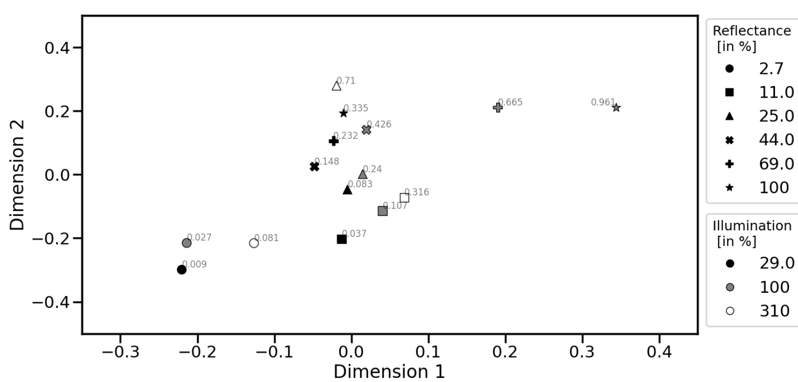


Figure 33: Ordinal embedding of observer 2 for the lightness task in the Physically Realistic condition with surround reflectance 2%.

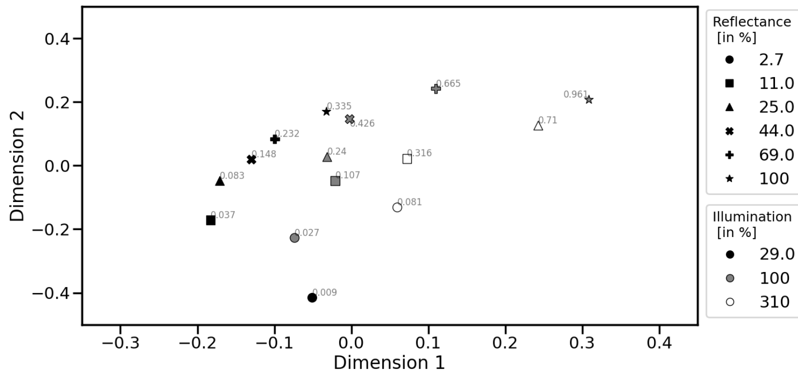


Figure 34: Ordinal embedding of observer 2 for the brightness task in the Physically Realistic condition with surround reflectance 2%.

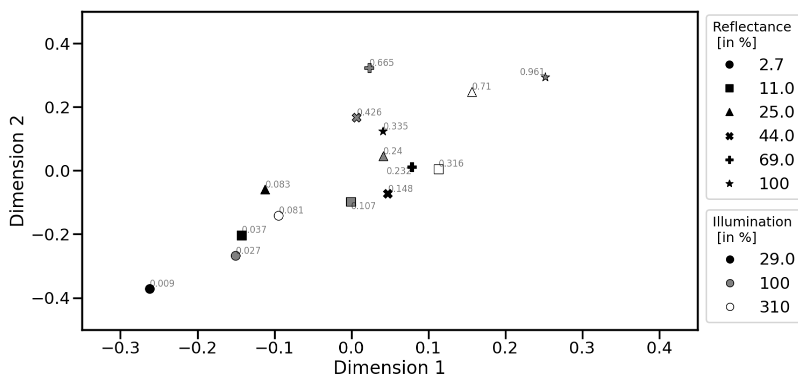


Figure 35: Ordinal embedding of observer 3 for the lightness task in the Physically Realistic condition with surround reflectance 0%.

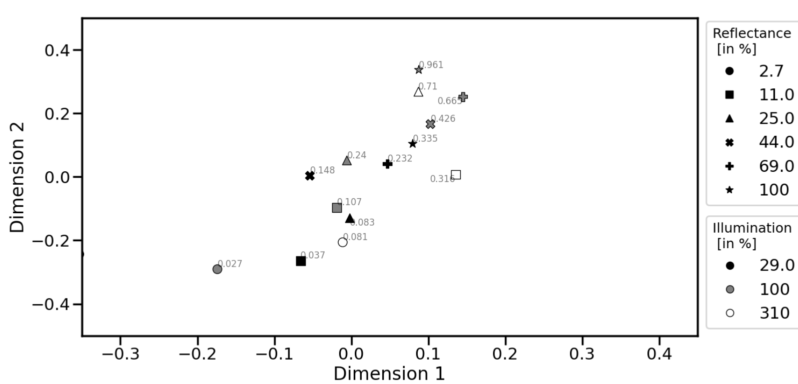


Figure 36: Ordinal embedding of observer 3 for the brightness task in the Physically Realistic condition with surround reflectance 0%.

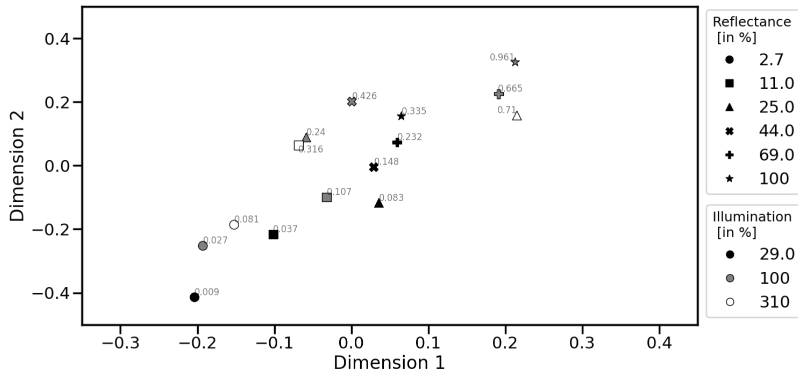


Figure 37: Ordinal embedding of observer 3 for the lightness task in the Physically Realistic condition with surround reflectance 2%.

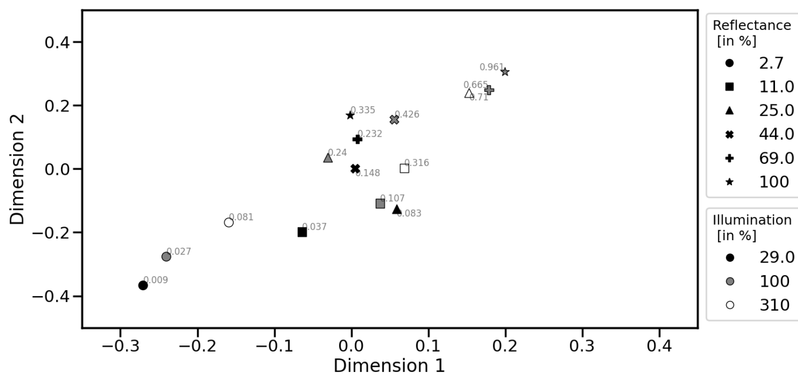


Figure 38: Ordinal embedding of observer 3 for the brightness task in the Physically Realistic condition with surround reflectance 2%.

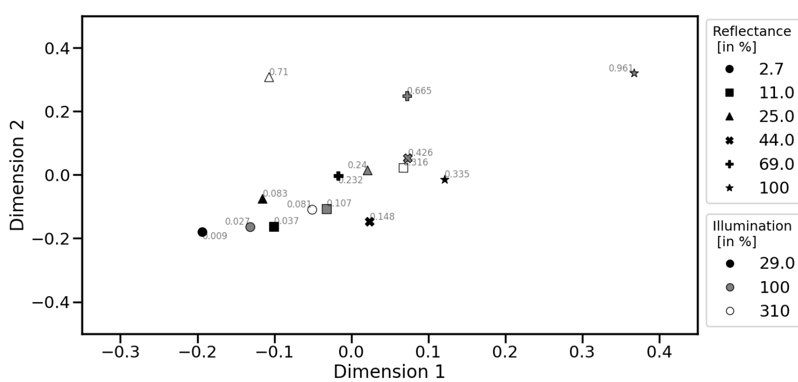


Figure 39: Ordinal embedding of observer 4 for the lightness task in the Physically Realistic condition with surround reflectance 0%.

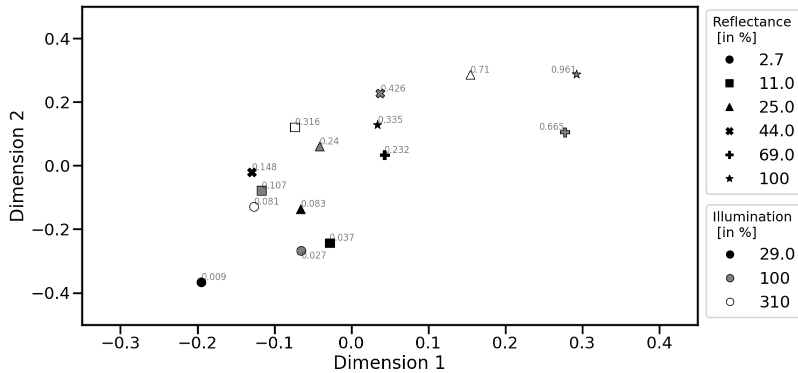


Figure 40: Ordinal embedding of observer 4 for the brightness task in the Physically Realistic condition with surround reflectance 0%.

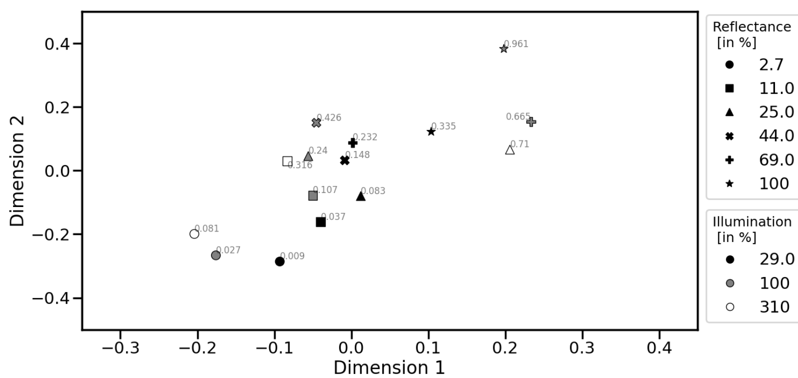


Figure 41: Ordinal embedding of observer 4 for the lightness task in the Physically Realistic condition with surround reflectance 2%.

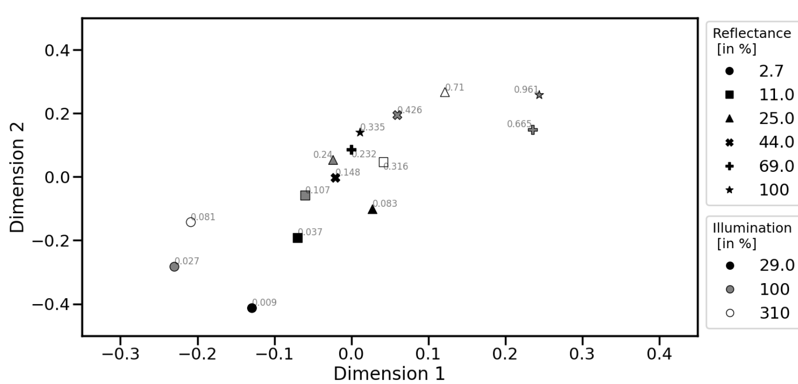


Figure 42: Ordinal embedding of observer 4 for the brightness task in the Physically Realistic condition with surround reflectance 2%.

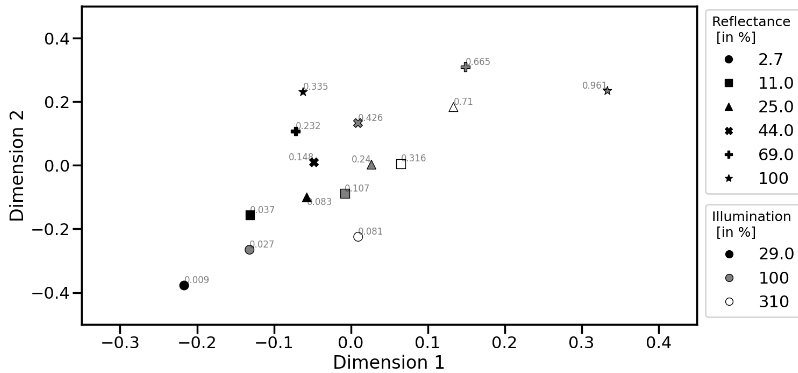


Figure 43: Ordinal embedding of observer 5 for the lightness task in the Physically Realistic condition with surround reflectance 0%.

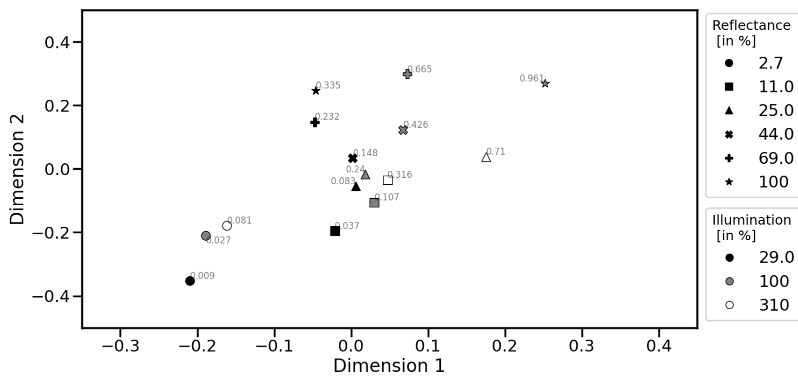


Figure 44: Ordinal embedding of observer 5 for the lightness task in the Physically Realistic condition with surround reflectance 2%.

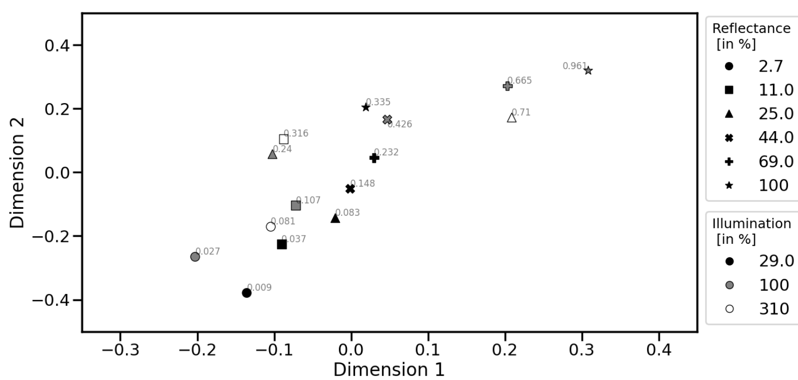


Figure 45: Ordinal embedding of observer 6 for the lightness task in the Physically Realistic condition with surround reflectance 0%.

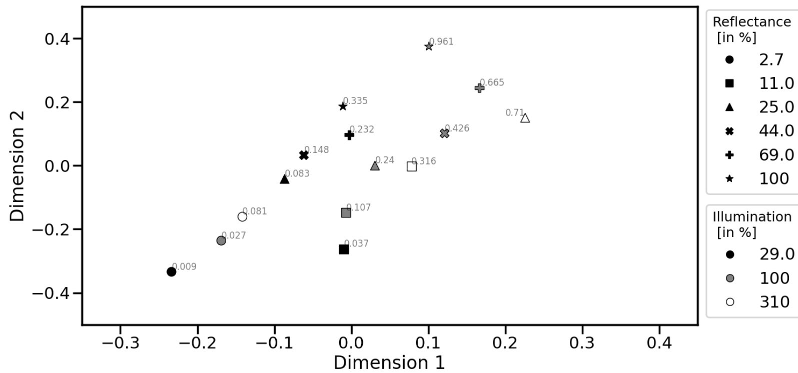


Figure 46: Ordinal embedding of observer 6 for the lightness task in the Physically Realistic condition with surround reflectance 2%.

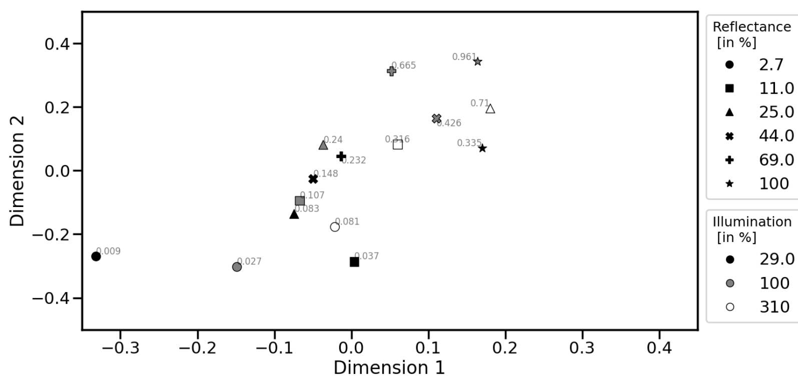


Figure 47: Ordinal embedding of observer 7 for the lightness task in the Physically Realistic condition with surround reflectance 0%.

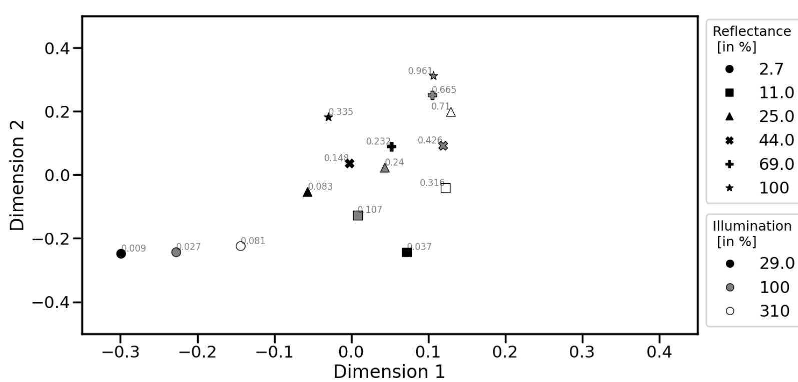


Figure 48: Ordinal embedding of observer 7 for the lightness task in the Physically Realistic condition with surround reflectance 2%.

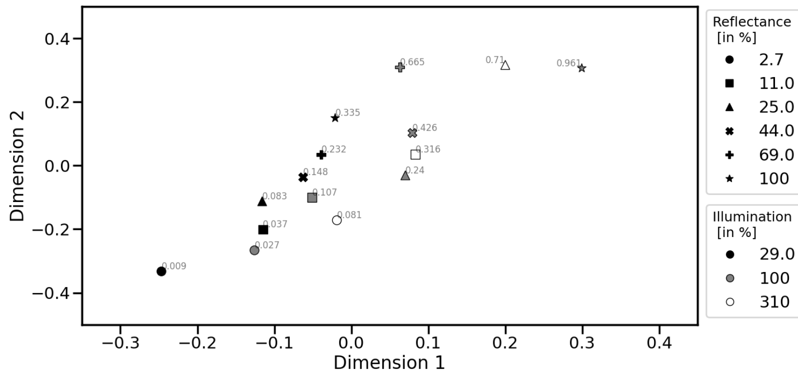


Figure 49: Ordinal embedding of observer 8 for the lightness task in the Physically Realistic condition with surround reflectance 0%.

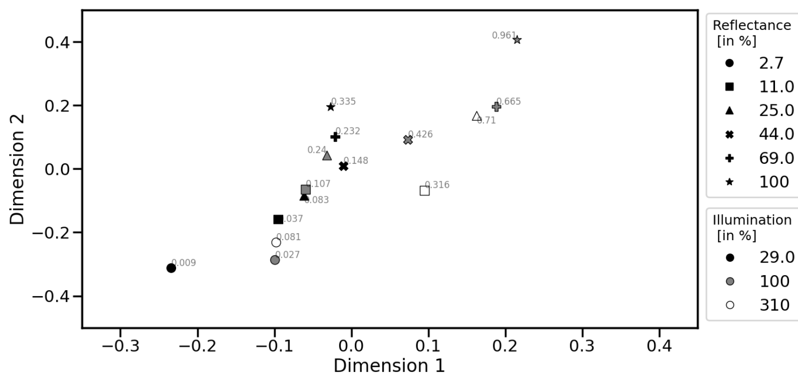


Figure 50: Ordinal embedding of observer 8 for the lightness task in the Physically Realistic condition with surround reflectance 2%.